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# A New Test on Asset Return Predictability with Structural Breaks

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## Abstract

This article considers predictive regressions in which a structural break is allowed on an unknown date. We establish novel testing procedures for asset return predictability using empirical likelihood (EL) methods based on weighted score equations. The theoretical results are useful in practice because our unified framework does not require distinguishing whether the predictor variables are stationary or nonstationary. Monte Carlo simulation studies show that the EL-based tests perform well in terms of size and power in finite samples. Finally, as an empirical analysis, we test the predictability of the monthly S&P 500 value-weighted log excess return using various predictor variables.

**Key words:** autoregressive process, empirical likelihood, structural break, unit root, weighted estimation

**JEL classification:** C12, C14, C32, G12

Asset return predictability has been studied for decades as a cornerstone research topic in economics and finance. It has been widely examined in many financial applications, such as mutual fund performance, conditional capital asset pricing, and optimal asset allocations. There are two major facets to dealing with asset returns predictability: first, checking whether the return series is autocorrelated, a random walk, or a martingale difference sequence (MDS), and second, using financial (state) variables as predictors to determine whether the financial (state) variables can predict asset returns. There is a vast amount of literature devoted to testing whether asset returns are autocorrelated, random walk, MDS, or other types of dependent structures; see Campbell, Lo, and Mackinlay (1997) and the references therein). Recently, numerous empirical studies have documented the predictability of asset returns using various lagged financial or state variables, such as the log dividend-price ratio, log earnings-price ratio, log book-to-market ratio, dividend yield, term spread, default premium, interest rates, and other economic variables: see, to name a few, Fama (1970); Keim and Stambaugh (1986); Campbell and Shiller (1988); Fama and French (1988); Lettau and Ludvigson (2001); Campbell and Yogo (2006); Goyal and Welch (2008); Kostakis, Magdalinos, and Stamatogiannis (2015); and the references therein. Although much research has been conducted, empirical evidence remains inconclusive.

Predictive regression is a conventional method used to check whether some financial variables have explanatory power for stock return predictability. A linear predictive regression system is specified as follows:

$$\begin{cases} y_t = \alpha + \beta x_{t-1} + u_t, \\ x_t = \theta + \phi x_{t-1} + v_t \end{cases} \tag{1}$$

for $1 \leq t \leq T$, where $|\phi| < 1$, $u_t = \rho v_t + \epsilon_t$, $(\epsilon_t, v_t) \sim N(0, \text{diag}(\sigma_\epsilon^2, \sigma_v^2))$ are independent and identically distributed (i.i.d.) series and $x_0 \sim N(\theta(1-\phi)^{-1}, \sigma_v^2(1-\phi^2)^{-1})$. In a predictive regression, the future values of some scalar time series $y_t$ can be predicted from the lagged values of a financial variable $x_{t-1}$. Therefore, the null hypothesis is no predictability; that is, $\mathbb{H}_0 : \beta = 0$. Note that this normality assumption may not be required if the sample size $T$ is large enough.

Notably, predictive regressions contain econometric issues that have crucial effects on testing predictability. Campbell (2008), Phillips and Lee (2013), and Phillips (2015) gave an overview of econometric issues and remedies in predictive regressions. Here, we briefly review their arguments for completeness. First, the correlation between $u_t$ and $v_t$ plays an important role in many applications; see Table 4 in Campbell and Yogo (2006), which creates the so-called "embedded endogeneity." Stambaugh (1999) showed that the ordinary least squares (OLS) estimator for $\beta$ in Equation (1) is biased in finite samples due to the correlation between $u_t$ and $v_t$ under normality and with stationary regression ($|\phi| < 1$), denoted by I(0). More precisely, the bias of the OLS estimator $\hat{\beta}$ can be represented as

$$\mathbb{E}[\hat{\beta} - \beta] = \rho \mathbb{E}[\hat{\phi} - \phi],$$

where $\rho = \text{cov}(u_t, v_t)/\text{var}(v_t)$. The autoregressive bias function $\mathbb{E}[\hat{\phi} - \phi]$ depends only on $\phi$ and the sample size $T$. Thus, the sample autocorrelation is biased downward about $-(1 + 3\phi)/T$, and the predictive slope $\beta$ is biased upward with $\rho < 0$. Stambaugh (1999) suggested the first-order bias-correction estimator, while Amihud and Hurvich (2004) considered a linear projection of $u_t$ on $v_t$ as $u_t = \rho v_t + \epsilon_t$ and then, regressed $y_t$ on $\hat{v}_t$ and $x_{t-1}$ with intercept; that is,

$$y_t = \alpha + \beta x_{t-1} + \rho \hat{v}_t + \epsilon_t, \tag{2}$$

where $\hat{v}_t$ is obtained from the second equation in Equation (1). The OLS estimator of $\beta$, denoted by $\hat{\beta}$, is a two-stage approach. However, Amihud and Hurvich (2004) assumed that $x_t$ is stationary.

Second, the autoregressive parameter $\phi$ in $x_t$ is allowed to be persistent, which is crucial for a statistical inference on $\beta$. Important contributions about nearly integrated or integrated regressors include, but not limited to, Phillips (1987); Elliott and Stock (1994); Cavanagh, Elliott, and Stock (1995); Lewellen (2004); Torous, Valkanov, and Yan (2004); Campbell and Yogo (2006); Jansson and Moreira (2006); Amihud, Hurvich, and Wang (2009); Chen and Deo (2009); Cai and Wang (2014); and the references therein. In the literature, a persistent regressor $x_t$ is represented in a local-to-unity framework; that is, $\phi = 1 - c/T, c \geq 0$, denoted by NI(1) if $c > 0$ or I(1) if $c = 0$. Indeed, Cai and Wang (2014) showed that $\hat{\beta}$ in Equation (2) has the following asymptotic distribution $T(\hat{\beta} - \beta) \xrightarrow{d} \xi_c$ where $\xi_c$ is a random variable involving the integration of a geometric Brownian motion and "$\xrightarrow{d}$" denotes convergence in distribution; see Cai and Wang (2014) for details. Therefore, the asymptotic results, in particular the limiting distribution, depend on $c$, which is not estimable consistently, although its estimate has a limiting distribution.

Recently, a series of studies have considered some uniform inferences on predictive regressions in the sense that the testing procedure for predictability is robust to general time-series characteristics on the regressor and errors. These include, but not limited to, the papers by Campbell and Yogo (2006); Phillips and Magdalinos (2007, 2009); Chen and Deo (2009); Elliott (2011); Phillips and Lee (2013); Zhu, Cai, and Peng (2014); Kostakis, Magdalinos, and Stamatogiannis (2015); Breitung and Demetrescu (2015); Lee (2016); Fan and Lee (2019); Liu et al. (2019); Yang et al. (2020); Hosseinkouchack and Demetrescu (2021); Yang et al. (2021); Demetrescu and Rodrigues (2022); Cai et al. (2023); Xu and Guo (2022); Zhu et al. (2023); and Liu et al. (2023). The reader is referred to the recent survey paper by Liao, Cai, and Chen (2018) for more discussions. Actually, Campbell and Yogo (2006) proposed a new method called the $Q$-test based on the Bonferroni idea to construct a confidence interval for $\beta$ for each $\phi$. Chen and Deo (2009) found that the intercept parameter in predictive regression with persistent covariates makes inference difficult, and they proposed the restricted likelihood method, which is free of such nuisance intercept parameters. More importantly, the bias of the restricted maximum likelihood estimates is much less than that of the OLS estimates near the unit root without loss of efficiency. Phillips and Magdalinos (2009) and Kostakis, Magdalinos, and Stamatogiannis (2015) introduced a data-filtering procedure called IVX estimation, which restricts the degree of persistence of data-filtered IVX instruments within the class of near-stationary process defined in Phillips and Magdalinos (2007). A standard instrumental variable estimation with the constructed instruments is robust to the general time-series characteristics of regressors in the sense that the derived estimator converges in distribution to a mixed normal limit. Hence, the corresponding Wald statistic asymptotically follows the chi-square distribution under the null. Phillips and Lee (2013) considered the IVX estimation to long-horizon predictive regressions with persistent covariates, while Lee (2016) and Fan and Lee (2019) extended the IVX filtering method to predictive quantile regression, and recently, the IVX method was further extended by Xu and Guo (2022) to the IVX Lagrange-multipliers test, respectively. Finally, Zhu, Cai, and Peng (2014) proposed an empirical likelihood (EL) approach together with a weighted least squares idea to construct a confidence interval for $\beta$, recently, extended by Liu et al. (2019, 2023) and Yang et al. (2021) to various scenarios.

In this line of work, predictive regression models investigated in the aforementioned literature are assumed to be stable; that is, no structural breaks are allowed. However, as Stock and Watson (1996) and Lettau and Van Nieuwerburgh (2008) found, economic and financial variables are subject to smooth or structural changes, which makes it reasonable to allow for the possibility of structural changes in predictive regression models. Subsequent research formally considered structural breaks in the predictive regressions. For example, Viceira (1997), Paye and Timmermann (2006), Rapach and Wohar (2006), and Zhu et al. (2023) tested for structural breaks and found strong evidence of instability in predictive regression models. Lettau and Van Nieuwerburgh (2008) focused on level shifts in the predictor variables and explained that the forecasting relationship may be unstable unless such shifts are included in the analysis. Recently, Cai, Wang, and Wang (2015) considered a model with coefficients changing smoothly over time, and then proposed a non-parametric testing procedure to determine whether the time-varying coefficients change over time. They found that the coefficients were indeed unstable. Recently, Gonzalo and Pitarakis (2012, 2017) and Zhu et al. (2023) developed tests for the null hypothesis of no predictability against threshold predictability in a predictive regression model with threshold effects. A practical question is how to specify the form of time-varying coefficients; that is, how the coefficients change over time. In this study, we assume that the coefficients are piecewise constant with structural changes. Since the work by Perron (1989), it is well known that structural changes in the data-generating process (DGP) should be considered appropriately to make statistical inferences reliable. Despite the large body of literature on estimating predictive regression models, studies pertaining to testing and estimating predictability allowing for structural changes are scarce.

The main contributions of this study are two-fold. First, we consider predictive regressions in which the model parameters exhibit a structural break on an unknown date. When the true break date is unknown, we estimate it and propose testing procedures for predictability based on a consistent estimate of the break fraction, which contrasts sharply with conventional predictability tests. To test for a structural break or parameter instability, important contributions include Andrews (1993) and Andrews and Ploberger (1994). Bai (1994, 1997) showed that the break fraction can be estimated consistently by minimizing the sum of squared residuals (SSRs) from the unrestricted model. They derived the limiting distribution of the estimate of the break date, which can be applied to constructing confidence intervals for the true break date. Bai and Perron (1998) and Bai and Perron (2003) considered statistical inference related to multiple structural changes under general conditions. Elliott and Müller (2006) considered the problem of testing for general types of parameter variations, including infrequent breaks, and established a partial-sums-type test based on the residuals obtained from the restricted model. The proposed tests were optimal as they nearly obtained the local Gaussian power envelop. The estimator of the break date is referenced in the literature, for instance, in Bai (1994, 1997); Bai and Perron (1998); Bai, Lumsdaine, and Stock (1998); and Kurozumi and Arai (2007a).

Second, we propose the EL method based on weighted score equations, first introduced by Zhu, Cai, and Peng (2014), without allowing for a structural break. Prior studies have considered weighted estimating procedures, and a normal limiting distribution has been obtained (see, e.g., Chan and Peng 2005; Ling 2005). Remarkably, Chan, Li, and Peng (2012) extended a weighted estimation method to first-order autoregression, denoted as AR(1), to estimate the autoregressive parameter and found that the estimate maintains a normal limit regardless of whether the autoregressive process is I(0), I(1), NI(1), or even explosive ($c < 0$). They suggested using the EL method for the weighted score equation of the weighted least squares estimate to construct confidence intervals for all values of the AR parameter and showed that confidence intervals obtained by the EL method perform better in finite samples than those constructed using the weighted least squares method proposed by So and Shin (1999).

Recently, Li, Chan, and Peng (2014) established EL tests for causality of bivariate first-order autoregressive processes. Zhu, Cai, and Peng (2014); Liu et al. (2019); Yang et al. (2021); and Liu et al. (2023), most relevant to this article, considered predictive regressions and applied EL methods to test the null hypothesis of $\beta = 0$ and constructed confidence intervals for $\beta$. Chan, Li, and Peng (2012) and Zhu, Cai, and Peng (2014) shed new light on predictive regressions as we can avoid estimating the autoregressive parameter $\phi$ and test for predictability based on the EL method, which performs well in finite samples.

In this study, we extend the analysis of Zhu, Cai, and Peng (2014) in a practical direction; that is, it is to test the instability of model parameters in predictive regressions and to show that the EL method based on some weighted score equations works well under such general circumstances. The simulation results indicate that the proposed EL tests have good finite-sample properties in terms of both size and power. To the best of our knowledge, this study is the first to incorporate an estimate of the break date and adopt a unified predictability test regardless of $x_t$ being stationary, nearly integrated, or unit root.

The remainder of this article is organized as follows. Section 1 introduces predictive regression models that exhibit a structural break on an unknown date. The EL-based methodologies are considered and useful asymptotic results are presented. Section 2 provides simulation results to support the usefulness of the proposed EL method. In Section 3, techniques are applied to test the predictability of stock returns using a variety of predictive regressors. Finally, Section 4 provides brief concluding remarks. All technical derivations are presented in Appendix A.

## 1 Econometric Approaches and Related Theories

We consider a linear predictive regression model that experiences a structural change on an unknown date. The standard model (1) is modified to allow for a structural change at date $T_1^0$ as follows: for $t = 1, \dots, T$,

$$\begin{cases} y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \le T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{t > T_1^0} + u_t, \\ x_t = \theta + \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}, \end{cases} \tag{3}$$

where, in what follows, the linear process $\sum_{j=0}^{\infty} \psi_j v_{t-j}$ is assumed to be strictly stationary,[1] so that $x_t$ is stable,[2] and $\{u_t, v_t\}$ is a sequence of i.i.d. random vectors with means zero and finite variances. To test the predictability of model (3), we first consider the joint null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ and propose a unified EL test regardless of whether $x_t$ is I(0) or

1 If $\{\psi_j\}$ in model (3) satisfies some condition, say $\sum_{j=0}^{\infty} |\psi_j| < \infty$, it is straightforward to show that $\sum_{j=0}^{\infty} \psi_j v_{t-j}$ is strictly stationary (see Brockwell and Davis 1991, p. 89).

2 Predictor variable $x_t$ in model (3) might be allowed to have breaks; that is, both parameters $\theta$ and $\phi$ are unstable. Indeed, Chang (2020) considered predictive regressions in which the predictor variable exhibits a level shift at some unknown date; that is, a change in $\theta$ and established testing procedure to test asset return predictability using empirical likelihood methods. Allowing structural breaks in the predictive regression with an unstable predictor in the empirical likelihood framework is a challenging problem and is warranted as a future research topic.

NI(1) or I(1). Moreover, we consider testing predictability in the pre- and post-break subsamples; that is, $\mathbb{H}_0 : \beta_1 = 0$ and $\mathbb{H}_0 : \beta_2 = 0$, respectively.

### 1.1 Testing the Joint Null Hypothesis $\mathbb{H}_0 : \boldsymbol{\beta}_1 = \boldsymbol{\beta}_2 = 0$

Note that the null hypothesis of interest is no predictability; that is, $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$. Under the null hypothesis, the predictive regression model in Equation (3) reduces to a change in mean model as follows:

$$y_t = \alpha_1 1_{t \le T_1^0} + \alpha_2 1_{t > T_1^0} + u_t. \tag{4}$$

Now, we state some assumptions as follows.

**Assumption 1** *The magnitude of the level shift can be expressed as* $|\alpha_2 - \alpha_1| = \delta_T T^{-1/2}$ *where* $\delta_T = O(T^{\epsilon})$ *for some* $\epsilon \in (0, 1/2]$.

**Assumption 2** $T_1^0 = [T\lambda_0]$ *where* $\lambda_0 \in (\pi, 1 - \pi)$ *for some* $\pi \in (0, 1/2)$.

Under Assumption 1, the magnitude of the level shift either is independent of the sample size or shrinks to zero at a rate slower than $T^{-1/2}$; thus, the break fraction can be estimated consistently regardless of whether $x_t$ is either stationary or (nearly) integrated under the null hypothesis (see, e.g., Bai 1994; Bai and Perron 1998; and Kurozumi and Arai, 2007a). Assumption 2 is the standard for ensuring that the pre- and post-break subsamples are asymptotically large enough. We propose a new testing procedure for the null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ as follows:

- Step 1: Estimate the break dates in the change in mean model (4) using the procedure recommended in Bai and Perron (1998, 2006).
- Step 2: Split the whole sample into disjoint subsamples in accordance with the estimated break dates.
- Step 3: Compute the EL-based test statistic in each subsample, and add them up to construct the final statistic.

The break date can be estimated using a global least squares criterion:

$$\hat{T}_1 = \underset{T_1 \in \Lambda}{\text{argmin}}\ S_T(T_1) \tag{5}$$

where $\Lambda = T\Lambda_\nu$, $\Lambda_\nu = (\nu, 1 - \nu)$ for some small trimming $\nu$, and $S_T(T_1)$ is the SSR specified as

$$S_T(T_1) = \sum_{t=1}^{T_1} \left( y_t - T_1^{-1} \sum_{t=1}^{T_1} y_t \right)^2 + \sum_{t=T_1+1}^{T} \left( y_t - (T - T_1)^{-1} \sum_{t=T_1}^{T} y_t \right)^2$$

for an admissible break date $T_1$. Let $\hat{\lambda}_1 = \hat{T}_1 / T$ denote the break fraction estimate. The consistency of $\hat{\lambda}$ is well-established in the literature.

**Remark 1** *If no level shift is allowed in Equation (3); that is,* $\alpha_1 = \alpha_2 = \alpha$. *Then,* $y_t = \alpha + u_t$ $(t = 1, \ldots, T)$ *under* $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$. *The EL method established by Zhu, Cai, and Peng (2014) can be applied to test the null hypothesis without modification. Hence, in this study, we focus on the change in mean model (4) under the null hypothesis.*

However, in both subsamples, the intercepts $\alpha_1$ and $\alpha_2$ are unknown, and the EL method may fail (see, e.g., Chan, Li, and Peng [2012]; Zhu, Cai, and Peng [2014] for a detailed explanation of this issue). To apply the EL method, we considered the following estimation equations:

$$\sum_{t=1}^{T_1^0}(y_t-\alpha_1-\beta_1 x_{t-1})=0, \sum_{t=1}^{T_1^0}(y_t-\alpha_1-\beta_1 x_{t-1})w(x_{t-1})=0, \quad (6)$$

and

$$\sum_{t=T_1^0+1}^{T}(y_t-\alpha_2-\beta_2 x_{t-1})=0, \sum_{t=T_1^0+1}^{T}(y_t-\alpha_2-\beta_2 x_{t-1})w(x_{t-1})=0, \quad (7)$$

where the weight $w(x_{t-1}) \equiv x_{t-1}/(1+x_{t-1}^2)^{1/2}$. Solving Equations (6) and (7) yields the weighted OLS estimates of $\alpha_j$ and $\beta_j$ for $j=1,2$. When $x_t$ is (nearly) integrated, $(T_1^0)^{-1}\sum_{t=1}^{T_1^0} u_t w(x_{t-1})$ does not converge in probability to a constant but converges in distribution to a random variable as $T \to \infty$ because of the intercept term (see, e.g., Chan and Wei 1987; Chan, Li, and Peng 2012). This suggests that the joint limit of $(T_1^0)^{-1/2}\sum_{t=1}^{T_1^0}(y_t-\alpha_1-\beta_1 x_{t-1})$ and $(T_1^0)^{-1/2}\sum_{t=1}^{T_1^0}(y_t-\alpha_1-\beta_1 x_{t-1})w(x_{t-1})$ cannot follow a bivariate normal distribution. Similarly, the joint limits of $(T-T_1^0)^{-1/2}\sum_{t=T_1^0+1}^{T}(y_t-\alpha_2-\beta_2 x_{t-1})$ and $(T-T_1^0)^{-1/2}\sum_{t=T_1^0+1}^{T}(y_t-\alpha_2-\beta_2 x_{t-1})w(x_{t-1})$ cannot be a bivariate normal distribution. Hence, when the predictor variable $x_t$ is non-stationary, the EL method based on weighted score equations fails as Wilks' theorem does not hold.

Zhu, Cai, and Peng (2014) suggested an avenue to avoid this problem. Here, we briefly review this argument. We can eliminate $\alpha_j, j=1,2$, using the first difference. However, this comes at a cost. When $\phi=1$, that is, $x_t$ is an I(1) process, the sequence $\{x_t-x_{t-1}\}$ is a stationary process. The inference of $\beta_j, j=1,2$, becomes less efficient with the first difference as the rate of convergence is $T^{1/2}$ rather than $T$ with an I(1) process $x_t$. Furthermore, the noise components, $\{u_t-u_{t-1}\}$, are not independent. To accommodate these difficulties, Zhu, Cai, and Peng (2014) used the first difference with a large lag. Let $m=[T/2]$,[3] where $T$ is the number of observations in the sample. The observables $\{y_t, x_t\}$ take the first difference with $m$-horizon differences. Then, we have $\tilde{y}_t=y_t-y_{t+m}$, $\tilde{x}_t=x_t-x_{t+m}$, and $\tilde{u}_t=u_t-u_{t+m}$ for $t=1,2,\ldots,m$. The EL function for $\beta_j, j=1,2$ can be constructed using $\tilde{y}_t$ and $\tilde{x}_t$.

The true break date $T_1^0$ is generally unknown. We use consistent estimates to apply the EL method. Without losing generality, we assume that $\hat{T}_1 < T_1^0$. Let $\hat{m}_1=[\hat{T}_1/2]$ and $\hat{m}_2=[(T-\hat{T}_1)/2]$. The difference series $\{\tilde{y}_t\}$ is obtained as follows for each subsample: (i) In the pre-$\hat{T}_1$ subsample, for $t=1,2,\ldots,\hat{m}_1$, we define $\tilde{y}_t=y_t-y_{t+\hat{m}_1}$, $\tilde{x}_t=x_t-x_{t+\hat{m}_1}$, and $\tilde{u}_t=u_t-u_{t+\hat{m}_1}$.

3 As pointed by a referee, the choice of $m$ is related to the test size and power. Ideally, one might consider a trade-off. But, for simplicity, the choice of $m=[T/2]$ is used commonly in the literature, see, for example, the papers by Zhu, Cai, and Peng (2014); Liu et al. (2019); Yang et al. (2021); and Liu et al. (2023). Therefore, we follow this convention.

$$\tilde{y}_t = \beta_1 \tilde{x}_{t-1} + \tilde{u}_t, \quad \tilde{x}_t = \phi \tilde{x}_{t-1} + \sum_{j=0}^{\infty} \psi_j \tilde{v}_{t-j}.$$

Taking the difference with a large lag helps ensure that $|\tilde{x}_t| \xrightarrow{p} \infty$ when $|x_t| \xrightarrow{p} \infty$ as $t \to \infty$ where "$\xrightarrow{p}$" denotes convergence in probability. (ii) In the post-$\hat{T}_1$ subsample, for $t = \hat{T}_1 + 1, \ldots, \hat{T}_1 + \hat{m}_2$, we define $\tilde{y}_t = y_t - y_{t+\hat{m}_2}$, $\tilde{x}_t = x_t - x_{t+\hat{m}_2}$, and $\tilde{u}_t = u_t - u_{t+\hat{m}_2}$. It is noteworthy that the post-$\hat{T}_1$ subsample should be divided into two parts if the estimate of the break date differs from the true break date, for instance, $\hat{T}_1 < T_1^0$. More precisely,

$$y_t = \begin{cases} \alpha_1 + \beta_1 x_{t-1} + u_t, & \text{for } t = \hat{T}_1 + 1, \ldots, T_1^0, \\ \alpha_2 + \beta_2 x_{t-1} + u_t, & \text{for } t = T_1^0 + 1, \ldots, T, \end{cases}$$

and

$$y_{t+\hat{m}_2} = \alpha_2 + \beta_2 x_{t-1} + u_t, \quad \text{for } t = \hat{T}_1 + 1, \ldots, \hat{T}_1 + \hat{m}_2.$$

Hence, we have

$$\tilde{y}_t = \beta_2 \tilde{x}_{t-1} + \tilde{u}_t, \quad \tilde{x}_t = \phi \tilde{x}_{t-1} + \sum_{j=0}^{\infty} \psi_j \tilde{v}_{t-j},$$

where

$$\tilde{u}_t = \begin{cases} (u_t - u_{t+\hat{m}_2}) + (\alpha_1 - \alpha_2) + (\beta_1 - \beta_2) x_{t-1}, & \text{for } t = \hat{T}_1 + 1, \ldots, T_1^0, \\ (u_t - u_{t+\hat{m}_2}) & \text{for } t = T_1^0 + 1, \ldots, \hat{T}_1 + \hat{m}_2. \end{cases}$$

Correspondingly, we let $\tilde{l}_1(\beta_1)$ denote the EL-based statistics calculated using data for $t = 1, \ldots, \hat{T}_1$ and $\tilde{l}_2(\beta_2)$ using data for $t = \hat{T}_1 + 1, \ldots, T$. More precisely, based on the preceding equations, the EL function is defined as

$$\tilde{L}_1(\beta_1) = \sup\left\{ \prod_{t=1}^{\hat{m}_1} (\hat{m}_1 p_t) : p_1 \geq 0, \ldots, p_{\hat{m}_1} \geq 0, \sum_{t=1}^{\hat{m}_1} p_t = 1, \sum_{t=1}^{\hat{m}_1} p_t \tilde{H}_t(\beta_1) = 0 \right\},$$

where $\tilde{H}_t(\beta_1) = (\tilde{y}_t - \beta_1 \tilde{x}_{t-1}) \tilde{x}_{t-1} / (1 + \tilde{x}_{t-1}^2)^{1/2}$. Note that the supremum is taken with respect to $p_t$. After applying the Lagrange multiplier technique, we obtain

$$\tilde{l}_1(\beta_1) = -2 \log \tilde{L}_1(\beta_1) = 2 \sum_{t=1}^{\hat{m}_1} \log\{1 + \tilde{\lambda}_1 \tilde{H}_t(\beta_1)\},$$

where $\tilde{\lambda}_1 = \tilde{\lambda}_1(\beta_1)$ satisfies

$$\sum_{t=1}^{\hat{m}_1} \frac{\tilde{H}_t(\beta_1)}{1 + \tilde{\lambda}_1 \tilde{H}_t(\beta_1)} = 0.$$

Similarly,

$$\tilde{L}_2(\beta_2) = \sup\left\{ \prod_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} (\hat{m}_2 p_t) : p_{\hat{T}_1+1} \geq 0, \ldots, p_{\hat{T}_1+\hat{m}_2} \geq 0, \sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} p_t = 1, \sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} p_t \tilde{H}_t(\beta_2) = 0 \right\},$$

where $\tilde{H}_t(\beta_2) = (\tilde{y}_t - \beta_2 \tilde{x}_{t-1}) \tilde{x}_{t-1} / (1 + \tilde{x}_{t-1}^2)^{1/2}$ and

$$\tilde{l}_2(\beta_2) = -2\log\tilde{L}_2(\beta_2) = 2\sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2}\log\{1+\tilde{\lambda}_2\tilde{H}_t(\beta_2)\},$$

where $\tilde{\lambda}_2 = \tilde{\lambda}_2(\beta_2)$ satisfies

$$\sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2}\frac{\tilde{H}_t(\beta_2)}{1+\tilde{\lambda}_2\tilde{H}_t(\beta_2)} = 0.$$

To validate Wilks' theorem for the aforementioned EL method, we assume the following regularity condition:

**Condition A:** $\mathbf{E}[u_1]=0$, $\mathbf{E}[v_1]=0$, $\mathbf{E}[|u_1|^{2+\kappa}+|v_1|^{2+\kappa}] < \infty$ for some $\kappa > 0$, and $\{u_t, v_t\}$ is a sequence of i.i.d. random vectors.

**Theorem 1** *Under Assumptions 1 and 2, suppose that model (4) holds with coefficients* $\psi_j$ *satisfying that the linear process* $\sum_{j=0}^{\infty}\psi_j v_{t-j}$ *is a strictly stationary process, and either (i)* $|\phi| < 1$ *independent of T (stationary case), (ii)* $\phi = 1 - c/T$ *for some* $c > 0$ *(NI(1) case), or (iii)* $\phi = 1$ *(I(1) case). Then, under Condition A, we have* $\tilde{l}_\beta(\beta_{1,0},\beta_{2,0}) \equiv \tilde{l}_1(\beta_{1,0}) + \tilde{l}_2(\beta_{2,0}) \xrightarrow{d} \chi^2(2)$ *as* $T\to\infty$ *where* $(\beta_{1,0},\beta_{2,0})$ *denotes the true value of* $(\beta_1,\beta_2)$.

Theorem 1 states that a unified EL test rejects the null hypothesis of no predictability in both regimes $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ at significance level $\tau$ if $\tilde{l}_\beta(0,0) > \chi^2(2)_{1-\tau}$ where $\chi^2(2)_{1-\tau}$ denotes the $(1-\tau)$th quantile of a chi-squared distribution with two degrees of freedom. Confidence intervals/sets are frequently used in conjunction with point estimates to convey information about estimate uncertainty. Based on Theorem 1, the EL confidence set for $(\beta_{1,0},\beta_{2,0})$ at level $\tau$ can be obtained as follows:

$$\mathrm{CI}_\tau = \{(\beta_1,\beta_2) : \tilde{l}_\beta(\beta_1,\beta_2) \le \chi^2(2)_{1-\tau}\}.$$

Therefore, the implementation for constructing confidence sets is straightforward without estimating any additional quantity. Indeed, the function "*emplik*" in the R package (see Zhou 2023) can be employed to compute $\tilde{l}_1(\beta_1)$ and $\tilde{l}_2(\beta_2)$ as easily as in the simulation study below.

The following theorem states the power property of our proposed EL-based test. Especially, we consider the local alternative hypothesis departing from the null hypothesis.

**Theorem 2** *Suppose the same conditions of Theorem 1 hold. Then, we have as* $T\to\infty$ *that:*

- *For* $|\phi| < 1$ *independent of T (stationary case), under the local alternative hypothesis* $\mathbb{H}_1 : \beta_1 = \beta_{1,0} - bT^{-1/2}$ *for some constant* $b\in\mathbb{R}$,

$$\tilde{l}_1(\beta_1) \xrightarrow{d} \chi^2(v_{11}^2),$$

*where* $v_{11} = \Sigma^{-1/2}\gamma_{11}$ *with* $\gamma_{11} = b[(-(1-\phi^{m_1})/(1-\phi))\mu + (1-\phi^{m_1})\lim_{t\to\infty}\mathbf{E}[x_{t-1}]]$ *and* $\Sigma = \lim_{t\to\infty}\mathbf{E}[\tilde{H}_t(\beta_{1,0})^2]$. *Similarly, under the local alternative hypothesis* $\mathbb{H}_1 : \beta_2 = \beta_{2,0} - bT^{-1/2}$ *for some constant* $b\in\mathbb{R}$,

$$\tilde{l}_2(\beta_2) \xrightarrow{d} \chi^2(v_{12}^2),$$

*where* $v_{12} = \Sigma^{-1/2}\gamma_{12}$ *with* $\gamma_{12} = b[(-(1-\phi^{m_2})/(1-\phi))\mu + (1-\phi^{m_2})\lim_{t\to\infty}\mathbf{E}[x_{t-1}]]$ *and* $\Sigma = \lim_{t\to\infty}\mathbf{E}[\tilde{H}_t(\beta_{2,0})^2]$.

- *For* $\phi = 1 - c/T$ *for some* $c > 0$ *(NI(1) case), under the local alternative hypothesis* $\mathbb{H}_1 : \beta_1 = \beta_{1,0} - bT^{-1}$ *for some constant* $b \in \mathbb{R}$,

$$\tilde{l}_1(\beta_1) \xrightarrow{d} \chi^2(v_{21}^2),$$

*where* $v_{21} = \Sigma^{-1/2}\gamma_{21}$ *with* $\gamma_{21} = b[2K_b(\lambda_1/2) - K_b(\lambda_1)]$ *and* $K_b(r) = \int_0^r e^{-(r-s)b}\mathrm{d}W_u(s)$ *is a diffusion process and* $W_u(s)$ *is a one-dimensional Brownian motion with variance* $\sigma_u^2 = \mathrm{Var}(u_t) + 2\Omega_1$ *and* $\Omega_1 = \sum_{k=2}^{\infty}\mathbf{E}[u_1u_k]$. *Similarly, under the local alternative hypothesis* $\mathbb{H}_1 : \beta_2 = \beta_{2,0} - bT^{-1}$ *for some constant* $b \in \mathbb{R}$,

$$\tilde{l}_1(\beta_2) \xrightarrow{d} \chi^2(v_{22}^2),$$

*where* $v_{22} = \Sigma^{-1/2}\gamma_{22}$ *with* $\gamma_{22} = b[2K_b((1-\lambda_1)/2) - K_b(\lambda_1) - K_b(1)]$.

- *For* $\phi = 1$, *under the local alternative hypothesis* $\mathbb{H}_1 : \beta_1 = \beta_{1,0} - bT^{-1}$ *for some constant* $b \in \mathbb{R}$,

$$\tilde{l}_1(\beta_1) \xrightarrow{d} \chi^2(v_{31}^2),$$

*where* $v_{31} = \Sigma^{-1/2}\gamma_{31}$ *with* $\gamma_{31} = b[2K_b^*(\lambda_1/2) - K_b^*(1)]$ *and* $K_b^*(r) = \Xi\int_0^r W_u(s)\mathrm{d}s$ *with* $\Xi = \sigma_v\sum_{j=0}^{\infty}\psi_j = \sigma_v\psi(1)$. *Similarly, under the local alternative hypothesis* $\mathbb{H}_1 : \beta_2 = \beta_{2,0} - bT^{-1}$ *for some constant* $b \in \mathbb{R}$,

$$\tilde{l}_1(\beta_2) \xrightarrow{d} \chi^2(v_{32}^2),$$

*where* $v_{32} = \Sigma^{-1/2}\gamma_{32}$ *with* $\gamma_{32} = b[2K_b^*((1-\lambda_1)/2) - K_b^*(\lambda_1) - K_b^*(1)]$.

## 1.2 Testing Predictability Allowing for a Structural Break

If the joint null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ is rejected, then it is likely that at least one of the regression coefficients $(\beta_1, \beta_2)$ is non-zero, which supports stock return predictability in a certain regime.

To test the null hypothesis of no predictability, allowing for a structural change on an unknown date $T_1^0$, we can rewrite the predictive regression (3) as follows:

$$y_t = z'_{t-1}\gamma_1 1_{t\le T_1^0} + z'_{t-1}\gamma_2 1_{t>T_1^0} + u_t, \quad t = 1, \ldots, T, \tag{8}$$

where $z_{t-1} = (1, x_{t-1})'$ and $\gamma_i = (\alpha_i, \beta_i)'$ for $i = 1, 2$. The magnitude of the change is denoted by $||\gamma_2 - \gamma_1|| = ||\delta|| \neq 0$ where the notation $||\cdot||$ denotes the Euclidean norm; that is, $||k|| = (\sum_{i=1}^m k_i^2)^{1/2}$ for $k \in \mathbb{R}^m$. To establish the consistency of the estimated break fraction $\hat{\lambda}$, we require the following assumption.

**Assumption 3** *The magnitude of the level shift can be expressed as* $||\gamma_2 - \gamma_1|| = ||\delta|| = \delta_T T^{-1/2}$ *where* $\delta_T = O(T^\epsilon)$ *for some* $\epsilon \in (0, 1/2]$.

Although Assumption 3 is particularly well suited to an adequate approximation of the exact distribution when the predictor variable $x_t$ is stationary, it remains adequate for non-stationary predictor variables (see Bai, Lumsdaine, and Stock 1998; Bai and Perron 1998; Kurozumi and Arai, 2007a). As explained in Elliott and Müller (2007), the break is sufficiently large to be detected with probability 1 with any reasonable test for breaks and to estimate its date in terms of the fraction of the sample consistently under Assumption 3. They considered a small break, $|\beta_2 - \beta_1| = dT^{-1/2}$ with a constant $d$ in linear regression models and found that $\lambda_0$ is not consistently estimable when the regressors are stationary processes.

**Remark 2** *If the predictor variable* $x_t$ *is integrated, Assumption 3 can be relaxed to the case where* $|\beta_2 - \beta_1| = \delta_T T^{-1}$; *that is, the magnitude of the slope change shrinks to zero at a rate faster than* $T^{-1/2}$. *As addressed in Bai, Lumsdaine, and Stock (1998) and Kurozumi and Arai (2007a, 2007b), the break fraction can be consistently estimated with a significantly smaller shift in the cointegrating coefficients. In this study, we consider testing procedures for stock return predictability regardless of whether the predictor variable is* $I(0)$ *or* $I(1)$, *thereby introducing Assumption 3.*

In matrix notation, we can rewrite predictive regression (8) as follows:

$$Y = \overline{X}_{T_1}\gamma + U.$$

For any matrix $A$, let $A'$ denote its transpose. Let $Y' = [y_1, \ldots, y_T]$, $U' = [u_1, \ldots, u_T]$, $\gamma = (\gamma_1', \gamma_2')'$, and $\overline{X}_{T_1} = [X_1(\lambda), X_2(\lambda)]$, where $X_1(\lambda)_t = z_{t-1}'$ if $t \leq T_1$ and zero otherwise, while $X_2(\lambda)_t = z_{t-1}'$ if $t > T_1$ and zero otherwise. The break date can be estimated using the global least-squares criterion:

$$\hat{T}_1 = \underset{T_1 \in \Lambda}{\operatorname{argmin}}\ Y'(I - P_{T_1})Y,$$

where $P_{T_1}$ is the matrix that projects on the range space of $\overline{X}_{T_1}$, that is, $P_{T_1} = \overline{X}_{T_1}(\overline{X}_{T_1}'\overline{X}_{T_1})^{-1}\overline{X}_{T_1}'$. The OLS estimate of the regression coefficient $\gamma$ is $\hat{\gamma} = (\overline{X}_{\hat{T}_1}'\overline{X}_{\hat{T}_1})^{-1}\overline{X}_{\hat{T}_1}'Y$, where $\overline{X}_{\hat{T}_1}$ is constructed with the estimate of the break date $\hat{T}_1$.

**Proposition 1** *Suppose Assumptions 2 and 3 hold true. Subsequently,* $\hat{\lambda} \xrightarrow{p} \lambda_0$ *as* $T \to \infty$.

Proposition 1 asserts that the estimated break fraction remains consistent, even when the magnitude of the break decreases as the sample size increases, regardless of whether the predictor variable $x_t$ is stationary or (nearly) integrated.

**Remark 3** *Allowing more than one break in predictive regression models is not difficult. However, because our main interest is to construct EL-based tests for predictability under general assumptions on the predictor variable and errors, the single break model is effective for delineating the results.*

**Remark 4** *There may be some concern about estimating a spurious break that does not exist in the DGP. Nunes, Kuan, and Newbold (1995) and Bai (1998) showed that the OLS estimate of the break date* $\hat{T}_1$ *is a spurious one when the error is an I(1) process. Kuan and Hsu (1998) and Hsu and Kuan (2008) considered a change in mean model for a fractionally integrated process and found that a spurious break can be estimated if memory parameter* $d^* \in (0, 1.5)$. *Recently, Chang and Perron (2016) considered a linear trend model with a change in slope with or without a concurrent level shift and showed that it is likely to estimate a spurious break when fractionally integrated errors have memory parameters in the interval* $(0, 1.5)$, *excluding the boundary case 0.5. In this study, the noise component* $(u_t, v_t)$ *is assumed to be i.i.d., which excludes the risk of estimating a spurious break. Furthermore,Proposition 1 confirms that the estimate of the break fraction is consistent, regardless of whether the regressor* $x_t$ *is I(0) or I(1).*

Without a loss of generality, we assume that $\hat{T}_1 < T_1^0$. Let $\hat{m}_1 = [\hat{T}_1/2]$ and $\hat{m}_2 = [(T - \hat{T}_1)/2]$. The difference series $\{\ddot{y}_t\}$ is obtained as follows for each subsample:

i. In the pre-$\hat{T}_1$ subsample, for $t = 1, 2, \ldots, \hat{m}_1$, we define $\ddot{y}_t = y_t - y_{t+\hat{m}_1}$, $\ddot{x}_t = x_t - x_{t+\hat{m}_1}$, and $\ddot{u}_t = u_t - u_{t+\hat{m}_1}$.

$$\ddot{y}_t = \beta_1 \ddot{x}_{t-1} + \ddot{u}_t.$$

ii. In the post-$\hat{T}_1$ subsample, for $t = \hat{T}_1 + 1, \ldots, \hat{T}_1 + \hat{m}_2$, we define $\ddot{y}_t = y_t - y_{t+\hat{m}_2}$, $\ddot{x}_t = x_t - x_{t+\hat{m}_2}$, and $\ddot{u}_t = u_t - u_{t+\hat{m}_2}$. Then,

$$y_t = \begin{cases} \alpha_1 + \beta_1 x_{t-1} + u_t, & \text{for } t = \hat{T}_1 + 1, \ldots, T_1^0, \\ \alpha_2 + \beta_2 x_{t-1} + u_t, & \text{for } t = T_1^0 + 1, \ldots, T, \end{cases}$$

and

$$y_{t+\hat{m}_2} = \alpha_2 + \beta_2 x_{t-1} + u_t, \quad t = \hat{T}_1 + 1, \ldots, \hat{T}_1 + \hat{m}_2,$$

from Proposition 1. Hence, we have

$$\ddot{y}_t = \beta_2 \ddot{x}_{t-1} + \ddot{u}_t,$$

where

$$\ddot{u}_t = \begin{cases} (u_t - u_{t+\hat{m}_2}) + (\alpha_1 - \alpha_2) + (\beta_1 - \beta_2) x_{t-1}, & \text{for } t = \hat{T}_1 + 1, \ldots, T_1^0, \\ (u_t - u_{t+\hat{m}_2}) & \text{for } t = T_1^0 + 1, \ldots, \hat{T}_1 + \hat{m}_2. \end{cases}$$

Based on the preceding equations, the EL function is defined as follows:

$$\ddot{L}_1(\beta_1) = \sup\left\{ \prod_{t=1}^{\hat{m}_1} (\hat{m}_1 p_t) : p_1 \geq 0, \ldots, p_{\hat{m}_1} \geq 0, \sum_{t=1}^{\hat{m}_1} p_t = 1, \sum_{t=1}^{\hat{m}_1} p_t \ddot{H}_t(\beta_1) = 0 \right\},$$

where $\ddot{H}_t(\beta_1) = (\ddot{y}_t - \beta_1 \ddot{x}_{t-1}) \ddot{x}_{t-1} / (1 + \ddot{x}_{t-1}^2)^{1/2}$. After applying the Lagrange multiplier technique, we obtain:

$$\ddot{l}_1(\beta_1) = -2\log \ddot{L}_1(\beta_1) = 2\sum_{t=1}^{\hat{m}_1} \log\{1+\ddot{\lambda}_1\ddot{H}_t(\beta_1)\},$$

where $\ddot{\lambda}_1 = \ddot{\lambda}_1(\beta_1)$ satisfies

$$\sum_{t=1}^{\hat{m}_1} \frac{\ddot{H}_t(\beta_1)}{1+\ddot{\lambda}_1\ddot{H}_t(\beta_1)} = 0.$$

Similarly,

$$\ddot{L}_2(\beta_2) = \sup\left\{\prod_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2}(\hat{m}_2 p_t) : p_{\hat{T}_1+1} \geq 0, \ldots, p_{\hat{T}_1+\hat{m}_2} \geq 0, \sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} p_t = 1, \sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} p_t \ddot{H}_t(\beta_2) = 0\right\},$$

where $\ddot{H}_t(\beta_2) = (\ddot{y}_t - \beta_2\ddot{x}_{t-1})\ddot{x}_{t-1}/(1+\ddot{x}_{t-1}^2)^{1/2}$, and

$$\ddot{l}_2(\beta_2) = -2\log \ddot{L}_2(\beta_2) = 2\sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} \log\{1+\ddot{\lambda}_2\ddot{H}_t(\beta_2)\},$$

where $\ddot{\lambda}_2 = \ddot{\lambda}_2(\beta_2)$ satisfies

$$\sum_{t=\hat{T}_1+1}^{\hat{T}_1+\hat{m}_2} \frac{\ddot{H}_t(\beta_2)}{1+\ddot{\lambda}_2\ddot{H}_t(\beta_2)} = 0.$$

The following theorem shows that Wilks' theorem holds for the proposed EL method. Proposition 1 is crucial for deriving the asymptotic results in Theorem 3.

**Theorem 3** *Under Assumptions 2 and 3, suppose that model (8) holds with coefficients $\psi_j$, satisfying that the linear process $\sum_{j=0}^{\infty}\psi_j v_{t-j}$ is a strictly stationary process, and either (i) $|\phi| < 1$ independent of $T$ (stationary case), (ii) $\phi = 1 - c/T$ for some $c > 0$ (NI(1) case), or (iii) $\phi = 1$ (I(1) case). Then, under Condition A, $\ddot{l}_1(\beta_{1,0})$ and $\ddot{l}_2(\beta_{2,0})$ converge in distribution to a chi-square limit with one degree of freedom as $T \to \infty$.*

According to Theorem 3, unified EL tests can be obtained for testing $\mathbb{H}_0 : \beta_1 = 0$ and $\mathbb{H}_0 : \beta_2 = 0$ for model (8) based on $\ddot{l}_1(0)$ and $\ddot{l}_2(0)$, respectively. Again, a unified interval set can be obtained using Theorem 3.

## 2 Monte Carlo Simulation Studies

In this section, we assess the finite sample properties of this procedure. We initially focus on the size properties of the test statistics. The DGP is given by Equation (3), with $\beta_1 = \beta_2 = 0$; that is,

$$y_t = \alpha_1 1_{t \leq T_1^0} + \alpha_2 1_{t > T_1^0} + u_t, \ (t = 1, \ldots, T),$$

as defined in Equation (4). The predictor variable, $x_t$, is specified by

$$x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j},$$

where the noise components $(u_t, v_t)$ are contemporaneously correlated as follows:

$$u_t = \rho v_t + \sqrt{1-\rho^2}\epsilon_t, \quad \rho = -0.95. \tag{9}$$

We choose either (i) $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$ or (ii) $\psi_j = 0.5^j$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$ and consider the standard normal distribution for the distributions of $(v_t, \epsilon_t)$ in Equation (9). We set the various parameters at the following values: $\alpha_1 = 0$, $\alpha_2 = aT^{-1/2}$ with $a \in \{4, 8, 12, 16\}$, $\lambda_0 \in \{0.5, 0.7\}$, and $\phi \in \{0.9, 1 - 2T^{-1}, 1\}$. In this configuration, the size is the rejection probability of the joint null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$. Three sample sizes, $T = 200, 500, 1000$, are considered to cover various time periods of real data and a set of level shifts with different magnitudes. For instance, with $a = 16$ and $T = 200$, the magnitude of the level shift $\alpha_2 \approx 1.13$, while $\alpha_2 \approx 0.13$ with $a = 4$ and $T = 1000$. As examined in Elliott and Müller (2007), Chang and Perron (2018), and Yamamoto (2018), it is required that the sample size be large enough to estimate relatively small breaks. The number of simulation replications is 5000 for each parameter combination. We use the R package "*emplik*" in Zhou (2023) to compute the EL function.

Tables 1 and 2 present the size properties of EL methods with a nominal size of 5%. The results regarding to the empirical size in the case of (i) $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$ are in Table 1. We observe that, for sample sizes $T \geq 500$, the EL tests have excellent size

**Table 1.** Finite sample sizes for the test based on Theorem 1 and model (3) with $\theta = 0$ and normally distributed errors for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$

| | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|
| $(a, \phi)$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ |
| (4, 0.9) | 0.069 | 0.074 | 0.061 | 0.061 | 0.056 | 0.050 |
| (8, 0.9) | 0.070 | 0.073 | 0.059 | 0.056 | 0.052 | 0.060 |
| (12, 0.9) | 0.059 | 0.056 | 0.050 | 0.054 | 0.054 | 0.053 |
| (16, 0.9) | 0.057 | 0.062 | 0.054 | 0.062 | 0.051 | 0.057 |
| $(4, 1 - 2T^{-1})$ | 0.070 | 0.091 | 0.065 | 0.080 | 0.058 | 0.068 |
| $(8, 1 - 2T^{-1})$ | 0.064 | 0.076 | 0.056 | 0.054 | 0.050 | 0.054 |
| $(12, 1 - 2T^{-1})$ | 0.062 | 0.058 | 0.049 | 0.049 | 0.046 | 0.049 |
| $(16, 1 - 2T^{-1})$ | 0.053 | 0.061 | 0.050 | 0.049 | 0.042 | 0.046 |
| (4, 1) | 0.085 | 0.093 | 0.075 | 0.076 | 0.067 | 0.076 |
| (8, 1) | 0.074 | 0.085 | 0.067 | 0.068 | 0.061 | 0.068 |
| (12, 1) | 0.070 | 0.077 | 0.065 | 0.072 | 0.058 | 0.064 |
| (16, 1) | 0.075 | 0.072 | 0.064 | 0.065 | 0.052 | 0.064 |

*Notes*: We take $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = \alpha_2 1_{t > [\lambda_0 T]} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_t$ with $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$, $\alpha_2 = aT^{-1/2}$ with $a \in \{4, 8, 12, 16\}$, and $\lambda_0 \in \{0.5, 0.7\}$. For the noise components, $v_t \sim$ i.i.d.$N(0, 1)$ and $u_t = \rho v_t + \sqrt{1-\rho^2}\epsilon_t$ with $\epsilon_t \sim$ i.i.d.$N(0, 1)$. Rejection frequencies are reported for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ with level 5% for the proposed empirical likelihood test $\tilde{l}_\beta(\beta_1, \beta_2)$.

**Table 2.** Finite sample sizes for the test based on Theorem 1 and model (3) with $\theta = 0$ and normally distributed errors for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$

| | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|
| $(a, \phi)$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ |
| (4, 0.9) | 0.069 | 0.072 | 0.060 | 0.066 | 0.054 | 0.056 |
| (8, 0.9) | 0.054 | 0.070 | 0.057 | 0.058 | 0.050 | 0.055 |
| (12, 0.9) | 0.058 | 0.060 | 0.051 | 0.062 | 0.056 | 0.050 |
| (16, 0.9) | 0.051 | 0.062 | 0.055 | 0.058 | 0.059 | 0.053 |
| $(4, 1 - 2T^{-1})$ | 0.076 | 0.086 | 0.063 | 0.070 | 0.055 | 0.063 |
| $(8, 1 - 2T^{-1})$ | 0.062 | 0.066 | 0.057 | 0.058 | 0.046 | 0.057 |
| $(12, 1 - 2T^{-1})$ | 0.057 | 0.065 | 0.051 | 0.053 | 0.044 | 0.047 |
| $(16, 1 - 2T^{-1})$ | 0.051 | 0.061 | 0.047 | 0.044 | 0.042 | 0.044 |
| (4, 1) | 0.082 | 0.092 | 0.080 | 0.072 | 0.071 | 0.078 |
| (8, 1) | 0.074 | 0.087 | 0.068 | 0.071 | 0.061 | 0.069 |
| (12, 1) | 0.074 | 0.077 | 0.064 | 0.063 | 0.062 | 0.058 |
| (16, 1) | 0.066 | 0.076 | 0.059 | 0.061 | 0.054 | 0.053 |

*Notes*: We take $\psi_j = 0.5^j$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = \alpha_2 1_{t>[\lambda^0 T]} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}$ with $\psi_j = 0.5^j$ for $j \geq 0$. The notes of Table 1 apply.

control across all values of $\phi$. This is particularly true for medium- and large-level shifts. For $T = 200$, EL methods appear to be oversized for small- and medium-level shifts. When $\phi = 1$, mild size distortion remains even for a large level shift ($a = 16$). Table 2 presents the results regarding the empirical size in the case of (ii) $\psi_j = 0.5^j$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. We find that the EL statistic shows size close to the nominal rate 5% apart from some mild oversizing for $T = 200$ and $\lambda_0 = 0.7$, particularly for $\phi = 1$.

Next, we examine the power performance of the test against the deviation from the null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$. The DGP is given by Equation (3):

$$y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{t > T_1^0} + u_t, \ (t = 1, \ldots, T).$$

Regarding the intercept terms, we set $\alpha_1 = 0$ and $\alpha_2 = 16T^{-1/2}$ (a single large-level shift). We consider two cases for the slope coefficients: $(b1)$ $\beta_1 = 0$, $\beta_2 = bT^{-1/2}$ and $(b2)$ $\beta_1 = \beta_2 = bT^{-1/2}$ where $b \in \{1, 2, 4, 8\}$. Note that the DGP is reduced to the conventional predictive regression without a structural break; that is, $y_t = \alpha + \beta x_{t-1} + u_t$, $(t = 1, \ldots, T)$ if $\alpha_1 = \alpha_2$ and $(b2)$ holds (see Zhu, Cai, and Peng [2014] for the finite sample performance of the EL-based tests). Tables 3 and 4 present the power properties of the EL method. The results for the empirical power in the case of (i) $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$ are listed in Table 3. In Panel (i), we consider the cases of $(b1)$ $\beta_1 = 0$ and $\beta_2 = bT^{-1/2}$. It is clear that the powers of the EL tests increase with the sample size $T$ and/or magnitude of the slope change $b$. In Panel (ii), we consider the case of $(b2)$ $\beta_1 = \beta_2 = bT^{-1/2}$ where the predictor variable shows the same predictability in the pre- and post-break subsamples. The proposed EL tests have overall satisfactory power and their powers increase as the alternative hypothesis is far from the null hypothesis. The test for the case of the NI(1) or I(1) is more powerful than that for the stationary case. Table 4 reports the results regarding the empirical

**Table 3.** Finite sample powers for the test based on Theorem 1 and model (3) with $\theta = 0$ and normally distributed errors for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$

| | | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|---|
| | | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ |
| (i) $(b1)$ holds | | | | | | | |
| $\phi = 0.9$ | $b = 1$ | 0.187 | 0.192 | 0.164 | 0.145 | 0.153 | 0.130 |
| | $b = 2$ | 0.478 | 0.361 | 0.470 | 0.325 | 0.478 | 0.304 |
| | $b = 4$ | 0.991 | 0.872 | 0.999 | 0.931 | 1.000 | 0.923 |
| | $b = 8$ | 1.000 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1 - 2T^{-1}$ | $b = 1$ | 0.563 | 0.414 | 0.868 | 0.599 | 0.977 | 0.807 |
| | $b = 2$ | 0.952 | 0.737 | 0.999 | 0.949 | 1.000 | 0.996 |
| | $b = 4$ | 0.999 | 0.986 | 1.000 | 0.999 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1$ | $b = 1$ | 0.681 | 0.505 | 0.916 | 0.676 | 0.986 | 0.847 |
| | $b = 2$ | 0.975 | 0.795 | 0.999 | 0.962 | 1.000 | 0.997 |
| | $b = 4$ | 1.000 | 0.990 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| (ii) $(b2)$ holds | | | | | | | |
| $\phi = 0.9$ | $b = 1$ | 0.262 | 0.305 | 0.261 | 0.266 | 0.249 | 0.266 |
| | $b = 2$ | 0.813 | 0.830 | 0.802 | 0.815 | 0.803 | 0.803 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1 - 2T^{-1}$ | $b = 1$ | 0.857 | 0.882 | 0.994 | 0.997 | 1.000 | 1.000 |
| | $b = 2$ | 0.999 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1$ | $b = 1$ | 0.944 | 0.951 | 0.998 | 0.998 | 1.000 | 1.000 |
| | $b = 2$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

*Notes*: We take $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{t > T_1^0} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_t$ with $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 1$. Regarding the intercept terms, we set $\alpha_1 = 0$ and $\alpha_2 = 16T^{-1/2}$ (a single large-level shift). As for slope coefficients, we consider two cases: $(b1)$ $\beta_1 = 0$, $\beta_2 = bT^{-1/2}$, and $(b2)$ $\beta_1 = \beta_2 = bT^{-1/2}$ where $b \in \{1, 2, 4, 8\}$. See notes in Table 1.

power in the case of (ii) $\psi_j = 0.5^j$ for $j \geq 0$ and shows patterns similar to those obtained in Table 3, indicating that our method is robust against the dependent or independent errors in modeling the predicting variable.

As addressed in Paye and Timmermann (2006) and Rapach and Wohar (2006), multiple structural breaks are empirically relevant. The DGP is specified as follows:

**Table 4.** Finite sample powers for the test based on Theorem 1 and model (3) with $\theta = 0$ and normally distributed errors for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$

| | | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|---|
| | | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ | $\lambda_0 = 0.5$ | $\lambda_0 = 0.7$ |
| (i) $(b1)$ holds | | | | | | | |
| $\phi = 0.9$ | $b = 1$ | 0.275 | 0.246 | 0.269 | 0.203 | 0.263 | 0.196 |
| | $b = 2$ | 0.832 | 0.586 | 0.863 | 0.589 | 0.853 | 0.588 |
| | $b = 4$ | 0.999 | 0.990 | 1.000 | 0.994 | 1.000 | 0.999 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1 - 2T^{-1}$ | $b = 1$ | 0.807 | 0.575 | 0.987 | 0.841 | 1.000 | 0.965 |
| | $b = 2$ | 0.994 | 0.915 | 1.000 | 0.996 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1$ | $b = 1$ | 0.875 | 0.631 | 0.993 | 0.867 | 0.999 | 0.977 |
| | $b = 2$ | 0.997 | 0.938 | 1.000 | 0.999 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 0.999 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| (ii) $(b2)$ holds | | | | | | | |
| $\phi = 0.9$ | $b = 1$ | 0.457 | 0.483 | 0.468 | 0.477 | 0.465 | 0.486 |
| | $b = 2$ | 0.999 | 0.998 | 0.998 | 0.999 | 0.996 | 0.997 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1 - 2T^{-1}$ | $b = 1$ | 0.991 | 0.994 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 2$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| $\phi = 1$ | $b = 1$ | 0.995 | 0.998 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 2$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 4$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| | $b = 8$ | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |

*Notes*: We take $\psi_j = 0.5^j$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{t > T_1^0} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}$ with $\psi_j = 0.5^j$ for $j \geq 0$. See notes in Tables 1 and 3.

$$\begin{cases} y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{T_1^0 < t \leq T_1^b} + \beta_3 x_{t-1} 1_{t > T_1^b} + u_t, \\ x_t = \theta + \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}. \end{cases} \tag{10}$$

We consider first the power performance of testing the null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ when the DGP has two structural breaks at $T_1^0 = [T\lambda_0]$ and $T_1^b = [T\lambda_b]$ with $\lambda_0 = 0.5$ and $\lambda_b = 0.75$. Moreover, we set $\alpha_1 = 0$, $\alpha_2 = 16T^{-1/2}$ (a single large-level shift), $\beta_1 = 0$, $\beta_2 = b_2 T^{-1/2}$ with $b_2 = \{2, 4\}$, and $\beta_3 = b_3 T^{-1/2}$ with $b_3 = \{2b_2, -b_2\}$. Table 5 presents the results for the empirical power of the test $\tilde{l}_\beta(\beta_{1,0}, \beta_{2,0})$. The simulation results show that the test has power even when the DGP contains two structural breaks. It is noteworthy that the power gets lower when the predictor variable is stationary and two breaks have opposite

**Table 5.** Finite sample powers for the test based on Theorem 1 and model (10) with $\lambda_0 = 0.5$, $\lambda_b = 0.75$, $\theta = 0$, and normally distributed errors for testing $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$

| | | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|---|
| | | $b_3 = 2b_2$ | $b_3 = -b_2$ | $b_3 = 2b_2$ | $b_3 = -b_2$ | $b_3 = 2b_2$ | $b_3 = -b_2$ |
| $\phi = 0.9$ | $b_2 = 2$ | 0.839 | 0.126 | 0.870 | 0.086 | 0.871 | 0.057 |
| | $b_2 = 4$ | 0.997 | 0.242 | 1.000 | 0.157 | 1.000 | 0.102 |
| $\phi = 1 - 2T^{-1}$ | $b_2 = 2$ | 0.888 | 0.481 | 0.923 | 0.682 | 0.948 | 0.804 |
| | $b_2 = 4$ | 0.929 | 0.719 | 0.946 | 0.871 | 0.970 | 0.933 |
| $\phi = 1$ | $b_2 = 2$ | 0.867 | 0.690 | 0.909 | 0.824 | 0.943 | 0.889 |
| | $b_2 = 4$ | 0.901 | 0.851 | 0.936 | 0.945 | 0.960 | 0.970 |

*Notes*: We take $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{T_1^b \geq t > T_1^0} + \beta_3 x_{t-1} 1_{t > T_1^b} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}$ with $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 0$. Note that two breaks occur at $T_1^0 = [T\lambda_0]$ and $T_1^b = [T\lambda_b]$ with $\lambda_0 = 0.5$ and $\lambda_b = 0.75$. We set $\alpha_1 = 0$, $\alpha_2 = 16T^{-1/2}$ (a single large-level shift), $\beta_1 = 0$, $\beta_2 = b_2 T^{-1/2}$ with $b_2 = \{2, 4\}$, $\beta_3 = b_3 T^{-1/2}$ with $b_3 = \{2b_2, -b_2\}$.

**Table 6.** Finite sample powers for the test based on Theorem 3 and model (10) with $\lambda_0 = 0.5$, $\lambda_b = 0.75$, $\theta = 0$, and normally distributed errors for testing $\mathbb{H}_{0,2} : \beta_2 = 0$ and $\mathbb{H}_{0,3} : \beta_3 = 0$

| | | $T = 200$ | | $T = 500$ | | $T = 1000$ | |
|---|---|---|---|---|---|---|---|
| | $(b_2, b_3)$ | $\mathbb{H}_{0,2}$ | $\mathbb{H}_{0,3}$ | $\mathbb{H}_{0,2}$ | $\mathbb{H}_{0,3}$ | $\mathbb{H}_{0,2}$ | $\mathbb{H}_{0,3}$ |
| $\phi = 0.9$ | (4, 0) | 0.850 | 0.097 | 0.928 | 0.084 | 0.955 | 0.091 |
| | (4, 2) | 0.819 | 0.402 | 0.880 | 0.317 | 0.904 | 0.306 |
| | (8, 2) | 0.994 | 0.238 | 1.000 | 0.196 | 1.000 | 0.211 |
| | (8, 4) | 0.983 | 0.787 | 0.992 | 0.826 | 0.992 | 0.821 |
| $\phi = 1 - 2T^{-1}$ | (4, 0) | 0.967 | 0.127 | 0.991 | 0.063 | 0.998 | 0.065 |
| | (4, 2) | 0.942 | 0.726 | 0.995 | 0.905 | 0.999 | 0.982 |
| | (8, 2) | 0.998 | 0.690 | 0.999 | 0.930 | 1.000 | 0.998 |
| | (8, 4) | 0.995 | 0.962 | 1.000 | 0.994 | 1.000 | 1.000 |
| $\phi = 1$ | (4, 0) | 0.961 | 0.101 | 0.999 | 0.076 | 0.997 | 0.078 |
| | (4, 2) | 0.978 | 0.746 | 0.995 | 0.955 | 0.999 | 0.992 |
| | (8, 2) | 0.999 | 0.761 | 1.000 | 0.966 | 1.000 | 0.996 |
| | (8, 4) | 0.998 | 0.986 | 1.000 | 1.000 | 1.000 | 1.000 |

*Notes*: We take $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 0$ in $\sum_{j=0}^{\infty} \psi_j v_{t-j}$. The DGP is $y_t = (\alpha_1 + \beta_1 x_{t-1}) 1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1}) 1_{T_1^b \geq t > T_1^0} + \beta_3 x_{t-1} 1_{t > T_1^b} + u_t$, where $x_t = \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}$ with $\psi_0 = 1$ and $\psi_j = 0$ for $j \geq 0$. Note that two breaks occur at $T_1^0 = [T\lambda_0]$ and $T_1^b = [T\lambda_b]$ with $\lambda_0 = 0.5$ and $\lambda_b = 0.75$. We set $\alpha_1 = 0$, $\alpha_2 = 4T^{-1/2}$, $\beta_1 = 0$, $\beta_2 = b_2 T^{-1/2}$ with $b_2 = \{4, 8\}$, and $\beta_3 = b_3 T^{-1/2}$ with $b_3 = \{0, 2, 4\}$.

signs, for instance, $\phi = 0.9$ and $b_3 = -b_2$. It may lead to the conclusion of no predictability falsely, thereby testing for and estimating multiple structural breaks can play an important role in predictive regressions.

We also consider the case in which the joint null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ has been rejected and two structural breaks exist in the DGP. Table 6 reports the power performance of the proposed tests in Theorem 3. We set $\alpha_1 = 0$, $\alpha_2 = 4T^{-1/2}$, $\beta_1 = 0$, $\beta_2 = b_2T^{-1/2}$ with $b_2 = \{4, 8\}$, and $\beta_3 = b_3T^{-1/2}$ with $b_3 = \{0, 2, 4\}$. Note that $b_3 = 0$ is for the size of the test. As expected, the test is more powerful as the magnitude of the break gets larger and the sample size increases. Simulation results uncover some interesting features. For example, it seems quite important to estimate the break dates correctly. When the magnitude of the break is large and there is a great difference in the magnitudes of two breaks, we can estimate the break dates precisely and the test is more powerful in a small sample. The test shows mild size distortions for testing $\mathbb{H}_{0,3} : \beta_3 = 0$ because we use the estimates of the break dates which are usually different from the true break dates.

Moreover, simulation experiments are devised to compare the finite sample performance of the EL tests with the IVX-based test. In contrast to the proposed EL method, the IVX-based test has neither test statistic nor its limiting distribution for the null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ in Equation (4). For a fair comparison, we consider the case with an unknown break date and test the null hypothesis $\mathbb{H}_0 : \beta_1 = 0$; that is, we test for stock return predictability in the pre-break subsample. We report the finite sample rejection frequencies of the IVX-based test by Kostakis, Magdalinos, and Stamatogiannis (2015) along with those of the EL test. Table 7 presents the size and power properties of the aforementioned tests.

The DGP is specified as follows: $y_t = (\alpha_1 + \beta_1 x_{t-1}) + u_t$, $x_t = \phi x_{t-1} + v_t$ with $\lambda_0 = 0.5$, $\alpha_1 = aT^{-1/2}$ with $a \in \{4, 8, 12, 16\}$, and $\beta_1 = bT^{-1/2}$ with $b \in \{0, 1, 2, 4, 8\}$. We first consider the case of $b = 0$ for size comparison. For the noise components, $v_t \sim$ i.i.d.$N(0, 1)$ and $u_t = \rho v_t + (1 - \rho^2)^{1/2}\epsilon_t$ with $\epsilon_t \sim$ i.i.d.$N(0, 1)$. The sample sizes are $T = 200, 500, 1000$. The proposed EL methods have empirical sizes close to the nominal level of 5%.

The IVX-based test reveals several interesting features. If the predictor variable $x_t$ is (nearly) integrated, the IVX-based test can be somewhat liberal because the finite sample rejection frequencies are above the nominal level of 5%. Size distortions for the IVX-based test remain, even when the sample size and magnitude of the level shift are relatively large. Overall, EL methods are remarkable in terms of size control, which confirms their validity, allowing a structural break in predictive regression. For $b > 0$, we examine the power properties of the aforementioned tests without size adjustment because there is no oversizing in the proposed EL tests. Surprisingly, the IVX-based test shows non-monotonic power against the alternative hypothesis of predictability such that the power of the test can decrease as the magnitude of change increases. For example, when $\phi = 0.9$, the power of the IVX-based test decreases as the magnitude of the break $b$ becomes greater than 2, regardless of the sample size. This finding highlights that the IVX-based test statistic may not be reliable when there exists at least a structural break in the predictive regressions.

**Remark 5** *Gonzalo and Pitarakis (2012, 2017) and Zhu et al. (2023) considered a predictive regression model with threshold effects. Under the alternative hypothesis $\mathbb{H}_1 : \beta_1 \neq 0$ or $\beta_2 \neq 0$, the DGPs contain a threshold (stationary) variable and an unknown threshold parameter. Recently, Zhu et al. (2023) investigated the local power properties of the proposed tests for two cases: a structural change with no thresholds, a threshold with no structural changes. Notably, the proposed test has some power if the data are generated by a structural change model. It is, however, not the case for a threshold model. It would be an important research topic to compare various test methods theoretically and empirically in predictive regressions because each test statistic is designed for some specific DGP under*

**Table 7.** Comparison of the EL test and IVX-based test for asset return predictability

| | $b=0$ | | $b=1$ | | $b=2$ | | $b=4$ | | $b=8$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| $(a, \phi)$ | IVX | EL | IVX | EL | IVX | EL | IVX | EL | IVX | EL |
| | | | | | $T=200$ | | | | | |
| (4, 0.9) | 0.073 | 0.050 | 0.193 | 0.124 | 0.404 | 0.387 | 0.412 | 0.838 | 0.479 | 0.993 |
| (8, 0.9) | 0.060 | 0.060 | 0.235 | 0.136 | 0.632 | 0.482 | 0.586 | 0.925 | 0.516 | 0.993 |
| (12, 0.9) | 0.045 | 0.059 | 0.245 | 0.133 | 0.778 | 0.495 | 0.780 | 0.968 | 0.592 | 0.996 |
| (16, 0.9) | 0.044 | 0.059 | 0.245 | 0.131 | 0.833 | 0.517 | 0.928 | 0.988 | 0.705 | 0.996 |
| $(4, 1-2T^{-1})$ | 0.093 | 0.055 | 0.376 | 0.319 | 0.482 | 0.719 | 0.640 | 0.955 | 0.772 | 0.999 |
| $(8, 1-2T^{-1})$ | 0.072 | 0.054 | 0.497 | 0.395 | 0.536 | 0.754 | 0.652 | 0.961 | 0.773 | 0.998 |
| $(12, 1-2T^{-1})$ | 0.066 | 0.058 | 0.622 | 0.476 | 0.631 | 0.794 | 0.692 | 0.958 | 0.786 | 0.998 |
| $(16, 1-2T^{-1})$ | 0.070 | 0.053 | 0.720 | 0.513 | 0.729 | 0.835 | 0.721 | 0.966 | 0.791 | 0.999 |
| (4, 1) | 0.090 | 0.054 | 0.520 | 0.460 | 0.665 | 0.824 | 0.802 | 0.972 | 0.886 | 0.999 |
| (8, 1) | 0.076 | 0.066 | 0.554 | 0.486 | 0.683 | 0.837 | 0.800 | 0.972 | 0.887 | 0.999 |
| (12, 1) | 0.079 | 0.067 | 0.633 | 0.543 | 0.704 | 0.841 | 0.818 | 0.972 | 0.899 | 0.999 |
| (16, 1) | 0.080 | 0.069 | 0.683 | 0.578 | 0.723 | 0.843 | 0.813 | 0.974 | 0.891 | 0.999 |
| | | | | | $T=500$ | | | | | |
| (4, 0.9) | 0.059 | 0.055 | 0.161 | 0.141 | 0.388 | 0.442 | 0.340 | 0.947 | 0.388 | 1.000 |
| (8, 0.9) | 0.041 | 0.050 | 0.229 | 0.150 | 0.692 | 0.508 | 0.520 | 0.992 | 0.405 | 1.000 |
| (12, 0.9) | 0.042 | 0.054 | 0.258 | 0.143 | 0.835 | 0.517 | 0.820 | 0.999 | 0.473 | 1.000 |
| (16, 0.9) | 0.041 | 0.057 | 0.254 | 0.147 | 0.858 | 0.533 | 0.963 | 1.000 | 0.605 | 1.000 |
| $(4, 1-2T^{-1})$ | 0.076 | 0.046 | 0.409 | 0.567 | 0.532 | 0.894 | 0.701 | 0.996 | 0.824 | 1.000 |
| $(8, 1-2T^{-1})$ | 0.068 | 0.046 | 0.512 | 0.627 | 0.575 | 0.902 | 0.728 | 0.997 | 0.832 | 1.000 |
| $(12, 1-2T^{-1})$ | 0.054 | 0.050 | 0.639 | 0.690 | 0.614 | 0.911 | 0.724 | 0.997 | 0.834 | 1.000 |
| $(16, 1-2T^{-1})$ | 0.066 | 0.046 | 0.736 | 0.761 | 0.692 | 0.924 | 0.724 | 0.998 | 0.836 | 1.000 |
| (4, 1) | 0.078 | 0.045 | 0.552 | 0.700 | 0.699 | 0.939 | 0.834 | 0.997 | 0.909 | 1.000 |
| (8, 1) | 0.063 | 0.055 | 0.590 | 0.702 | 0.721 | 0.928 | 0.840 | 0.998 | 0.903 | 1.000 |
| (12, 1) | 0.063 | 0.060 | 0.621 | 0.724 | 0.717 | 0.924 | 0.823 | 0.996 | 0.909 | 1.000 |
| (16, 1) | 0.068 | 0.057 | 0.667 | 0.767 | 0.731 | 0.943 | 0.835 | 0.997 | 0.910 | 1.000 |
| | | | | | $T=1000$ | | | | | |
| (4, 0.9) | 0.061 | 0.052 | 0.149 | 0.138 | 0.379 | 0.454 | 0.302 | 0.981 | 0.329 | 1.000 |
| (8, 0.9) | 0.043 | 0.484 | 0.228 | 0.165 | 0.680 | 0.511 | 0.501 | 0.997 | 0.341 | 1.000 |
| (12, 0.9) | 0.038 | 0.052 | 0.252 | 0.149 | 0.820 | 0.531 | 0.838 | 0.999 | 0.362 | 1.000 |
| (16, 0.9) | 0.037 | 0.043 | 0.254 | 0.168 | 0.848 | 0.543 | 0.979 | 1.000 | 0.506 | 1.000 |
| $(4, 1-2T^{-1})$ | 0.086 | 0.049 | 0.450 | 0.763 | 0.590 | 0.972 | 0.748 | 1.000 | 0.848 | 1.000 |
| $(8, 1-2T^{-1})$ | 0.068 | 0.043 | 0.503 | 0.776 | 0.595 | 0.977 | 0.752 | 1.000 | 0.844 | 1.000 |
| $(12, 1-2T^{-1})$ | 0.061 | 0.043 | 0.581 | 0.804 | 0.629 | 0.978 | 0.753 | 1.000 | 0.858 | 1.000 |
| $(16, 1-2T^{-1})$ | 0.057 | 0.045 | 0.687 | 0.851 | 0.674 | 0.980 | 0.772 | 1.000 | 0.857 | 1.000 |
| (4, 1) | 0.077 | 0.051 | 0.590 | 0.823 | 0.743 | 0.984 | 0.860 | 1.000 | 0.922 | 1.000 |
| (8, 1) | 0.052 | 0.058 | 0.608 | 0.828 | 0.739 | 0.985 | 0.863 | 1.000 | 0.923 | 1.000 |
| (12, 1) | 0.059 | 0.061 | 0.649 | 0.832 | 0.749 | 0.980 | 0.858 | 1.000 | 0.921 | 1.000 |
| (16, 1) | 0.065 | 0.063 | 0.663 | 0.850 | 0.766 | 0.980 | 0.862 | 1.000 | 0.925 | 1.000 |

*Notes*: The DGP is $y_t = (\alpha_1 + \beta_1 x_{t-1})1_{t \le T_1^0} + u_t$ and $x_t = \phi x_{t-1} + v_t$, where $\lambda_0 = 0.5$, $\alpha_1 = aT^{-1/2}$ with $a \in \{4, 8, 12, 16\}$, and $\beta_1 = bT^{-1/2}$ with $b \in \{0, 1, 2, 4, 8\}$. Note $b = 0$ for size comparison. For the noise components, $v_t \sim$ i.i.d.$N(0, 1)$ and $u_t = \rho v_t + \sqrt{1-\rho^2}\epsilon_t$ with $\epsilon_t \sim$ i.i.d.$N(0, 1)$. Rejection frequencies are reported for testing $\mathbb{H}_0 : \beta_1 = 0$ with level 5%.

*both the null and alternative hypotheses. A comprehensive set of simulations are inevitable to evaluate finite sample properties of test statistics in predictive regression, which is an object of our ongoing projects.*

In simulation experiments, we consider predictive regressions under practical assumptions on the predictor variable and errors: (i) there exists a structural break in the predictive regression model, (ii) the predictor variable can be stationary or non-stationary, and (iii) the errors $(u_t, v_t)$ are contemporaneously correlated. The simulation results appear to support the proposed EL methods having good finite sample properties in terms of both size and power. The results shed new light on testing for stock return predictability because the EL methods can help address various time-series characteristics of the predictor variable and incorporate a structural break on an unknown date in predictive regressions. Because the IVX-based test requires a complicated implementation and, more importantly, does not provide a theoretical justification for the joint null hypothesis of no predictability; that is, $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$, the proposed EL method can be a useful complement to testing for asset return predictability.

It is noteworthy that the powers of the EL tests are very close to 1 if the magnitude of the level shift is sufficiently large, $\alpha_2 = 16T^{-1/2}$, in the predictive regression. This result indicates that the magnitude of the change in predictive regression plays an important role in the finite sample properties of the proposed EL tests. For further investigation, the values of $\beta_1$ are allowed to range from $-1$ to 1 in increments of 0.1. For other parameters, we set $\beta_2 = 0$, $\rho = -0.95$, $\theta = 0$, $\phi = 0.99$, and $T = 150$. The noise components $(v_t, \epsilon_t) \sim$ i.i.d.$N(0, 1)$. The break date can be estimated by minimizing the SSR, as described in Equation (5). For the null hypothesis of $\beta_2 = 0$, rejection frequencies are shown in Figure 1. Because we set $\alpha_1 = \alpha_2 = 0$ in the DGP, the EL method with known $\alpha$, which is free from splitting the data into two parts, is well defined (labeled EL1) whereas the EL method with unknown $\alpha$, $\ddot{l}_2(\beta_2)$ allows for an irrelevant intercept (EL2). We simulate the following statistics: EL1 with $\hat{T}_1$, EL1 with $T_1^0$, EL2 with $\hat{T}_1$, and EL2 with $T_1^0$. The tests EL1 with $\hat{T}_1$ and EL2 with $\hat{T}_1$ suffer from some liberal size distortions unless $|\beta_1|$ is large. This suggests that the estimates $\hat{T}_1$ are variable when $|\beta_1|$ is not sufficiently large. This randomness translates into distributions of EL tests constructed with $\hat{T}_1$, which are far from the true break date case, and liberal size distortions occur. Compared with test EL2 with $\hat{T}_1$, test EL1 with $\hat{T}_1$, which uses the fact that the intercept terms $\alpha_1$ and $\alpha_2$ are known, is less affected by this problem, although some size distortions remain. The finite sample properties of EL methods emphasize that testing for and estimating the break date in the predictive regression is crucial to make EL tests statistically reliable.

## 3 Empirical Data Analysis

In this section, we apply the EL method to test stock return predictability. Specifically, the predictable variable $y_t$ is the monthly S&P 500 value-weighted log excess return, and the predictor variable $x_t$ includes the log dividend–price (*d/p*) ratio, log earnings–price (*e/p*) ratio, dividend yield (*dy*), book-to-market (*b/m*) ratio, Treasury bill rates (*tbl*), default yield spread (*dfy*), log dividend payout (*d/e*) ratio, net equity expansion (*ntis*), and term spread (*tms*). The dataset contains monthly data and spans 1927:01 to 2021:12; hence, the sample size is $T = 1140$. The monthly returns are computed by the difference between the S&P 500 index, including dividends, and the one-month Treasury bill rate. Data from Goyal

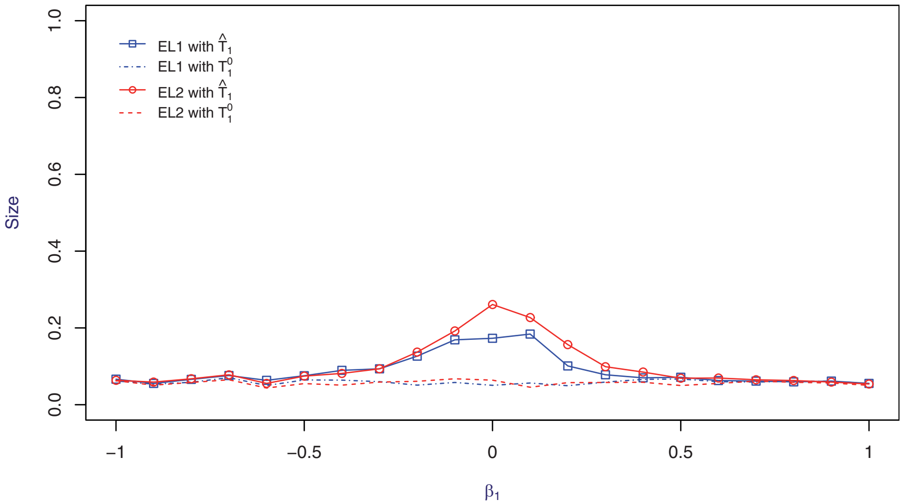


**Figure 1.** Rejection probabilities of EL tests for $\mathbb{H}_0 : \beta_2 = 0$.

*Note*: The DGP is $y_t = \beta_1 x_{t-1} 1_{t \leq [\lambda_0 T]} + u_t$ with $\lambda_0 = 0.5$, $x_t = 0.99 x_{t-1} + v_t$, $u_t = \rho v_t + (1-\rho^2)^{1/2} \epsilon_t$, $\rho = -0.95$, $(v_t, \epsilon_t) \sim$ i.i.d.$N(0,1)$, and $T = 150$. Rejection frequencies are reported for testing $\mathbb{H}_0 : \beta_2 = 0$ as $\beta_1$ varies from $-1$ to 1.

and Welch (2008) have been widely used in the predictive regression literature, such as Cenesizoglu and Timmermann (2008); Maynard, Shimotsu, and Wang (2011); Kostakis, Magdalinos, and Stamatogiannis (2015); Liu et al. (2019); and Lee (2016) and Fan and Lee (2019) in a quantile regression framework. Distinguished from existing methodologies such as Lewellen (2004), Campbell and Yogo (2006), and Cai and Wang (2014), it is unnecessary for EL methods to evaluate the persistence of the predictor variable $x_t$. In fact, based on unit root tests, both *d/p* and *e/p* ratios are I(1) or NI(1) processes (see Cai, Wang, and Wang 2015, for details).

Table 8 presents the EL test results where the $p$-values for testing $\mathbb{H}_0 : \beta = 0$ and $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ are reported. The EL2 statistic in Zhu, Cai, and Peng (2014) is designed to test the null hypothesis of no predictability $\mathbb{H}_0 : \beta = 0$ with an unknown intercept $\alpha$ whereby no level shift is allowed. The $\tilde{l}_\beta(\beta_1, \beta_2)$ statistic also tests the null hypothesis of no predictability, $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$, allowing for a level shift. As the former null hypothesis can be rejected because of different intercepts, we can infer whether the valuation ratios considered induce episodic predictability.

Specifically, we estimate the date of a level shift in the monthly S&P 500 value-weighted log excess return, 1942:03, and use it to implement $\tilde{l}_\beta(\beta_1, \beta_2)$. The results in bold indicate the rejection of the null hypothesis of no predictability at the 5% significance level. We find an interesting feature of Treasury-bill rates (*tbl*) as a predictor variable. EL2 cannot reject the null hypothesis $\mathbb{H}_0 : \beta = 0$, while the $\tilde{l}_\beta(\beta_1, \beta_2)$ statistic rejects the null hypothesis $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ with a $p$-value of 0.0146. This result strongly supports the idea that predictability is driven by the *tbl* predictor rather than a level shift. Recently, Kostakis, Magdalinos, and Stamatogiannis (2015) considered the sub-period 1952:01–2012:12 and found predictability for the predicting variables of T-bill (*tbl*) and term spread (*tms*) at the

**Table 8.** *p*-values of predictability tests on the S&P 500 excess returns (1927:01–2021:12).

| | EL2 $\mathbb{H}_0 : \beta = 0$ | $\tilde{l}_\beta(\beta_1, \beta_2)$ $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$ |
|---|---|---|
| *d/p* | 0.4465 | 0.8919 |
| *e/p* | 0.1976 | 0.7355 |
| *dy* | 0.3762 | 0.7624 |
| *b/m* | 0.1773 | 0.5382 |
| *tbl* | 0.3264 | **0.0146** |
| *dfy* | 0.7766 | 0.6786 |
| *d/e* | 0.8377 | 0.4763 |
| *ntis* | 0.1330 | 0.6005 |
| *tms* | 0.6171 | 0.2739 |

*Notes*: This table reports *p*-values of EL tests for the null hypothesis of no predictability. The predictor variables are the log dividend–price (*d/p*), log earnings–price (*e/p*) ratios, dividend yield (*dy*), book-to-market (*b/m*) ratio, Treasury-bill rate (*tbl*), default yield spread (*dfy*), log dividend-payout (*d/e*) ratio, net equity expansion (*ntis*), and term spread (*tms*). The EL2 statistics in Zhu, Cai, and Peng (2014) is designed to test the null hypothesis of no predictability, $\mathbb{H}_0 : \beta = 0$ with an unknown intercept $\alpha$ whereby no level shift is allowed. The $\tilde{l}_\beta(\beta_1, \beta_2)$ statistic also tests the null hypothesis of no predictability, $\mathbb{H}_0 : \beta_1 = \beta_2 = 0$, allowing for a level shift. We estimate the date of a level shift, 1942:04, and use it to implement $\tilde{l}_\beta(\beta_1, \beta_2)$. The results in bold indicate the rejection of the null hypothesis of no predictability at the 5% significance level.

10% significance level. The *Q*-test of Campbell and Yogo (2006) found that *tbl*, *tms*, and *dy* are marginally significant at the 10% level. As evidence that predictability has diminished in recent sample periods (see, e.g., Campbell and Yogo 2006), it is noteworthy that *tbl* has more information on stock return predictability. In addition, we consider the possibility of multiple breaks when the predictor variable $x_t$ is *tbl*. We estimate the second break date, 1979:06, and test the null hypothesis of no predictability in each subsample. EL tests for the null of no predictability $\mathbb{H}_{0,1} : \beta_1 = 0$, $\mathbb{H}_{0,2} : \beta_2 = 0$, and $\mathbb{H}_{0,3} : \beta_3 = 0$ have *p*-values of 0.7016, 0.0006, and 0.0923, respectively. It implies that *tbl* has predictability after the first break date, 1942:03, though it has diminished after the second break date, 1979:06.

By contrast, there is no evidence of predictability for the *d/p*, *e/p*, *dy*, *b/m*, *dfy*, *d/e*, *ntis*, and *tms* from the $\tilde{l}_\beta(\beta_1, \beta_2)$ statistics. For the period 1927:01–2012:12, the *Q*-test of Campbell and Yogo (2006) showed that *dy*, *bm*, and *ntis* are significant at the 10% level, while the IVX-based test of Kostakis, Magdalinos, and Stamatogiannis (2015) found that the null of no predictability can be rejected at the 5% level only for *e/p*, *b/m*, and *ntis* and at the 10% level for *dy*. The *Q*-test and IVX-based test are designed for persistent predictor variables without allowing for the possibility of a level shift in the predictive regression. In particular, the Bonferroni-type test (*Q*-test) is valid if the predictor variable is as persistent as a NI(1) process with strong assumptions, such as normality and known covariance of innovations. Hence, the test results based on existing methods may be misleading if a level shift exists. The empirical findings reveal the merits of EL methods that complement the existing methods.

Before finishing this section, we must briefly discuss the stationarity assumption for the predictor variables. To understand the implications of this assumption, we examine it in two different ways. From an economic perspective, the predictor variables should be stationary; that is, $|\phi| < 1$. Otherwise, an explosive bubble may exist in stock prices. In other words, the predicted variable cannot be stationary if the predictor variable is nonstationary, which is still a controversial topic in empirical studies. As noted in Lettau and Van Nieuwerburgh (2008), a level shift in the predictor variable is also a form of non-stationarity. From a statistical perspective, it is preferable to make tests reliable regardless of whether the predictor variables are stationary or non-stationary. However, the test results cannot identify the time-series characteristic of the predictor variable. Because it makes little sense to predict asset returns with an integrated process, further investigation of the predictor variable might be required (see also Liu et al. 2019).

## 4 Concluding Remarks

In this study, we consider predictive regression models in which model parameters exhibit a structural break on an unknown date and the predictor variable is allowed to be either stationary or (nearly) integrated. As addressed by Viceira (1997), Paye and Timmermann (2006), and Rapach and Wohar (2006), parameter instability in predictive regressions is a long-standing problem. The main contribution of this study to the literature is to provide a unified approach that is valid regardless of the time-series characteristics of the predictor variable when the model parameters are unstable in predictive regressions. We established novel testing procedures for asset return predictability using EL methods based on weighted score equations and studied their asymptotic distributions. The proposed methods are particularly useful because they allow us to distinguish predictability generated by a certain predictor variable from that induced by a permanent shift in level, and they require no prior knowledge as to (i) whether the predictor variable is stationary or non-stationary and (ii) whether the noise components are contemporaneously correlated or not, common cases in practice. Simulations have shown the usefulness of EL methods and demonstrated clear improvements over existing tests. Furthermore, an extension of practical interest is to generalize our model to analyze a large global dataset, which is useful for capturing the predictable component of stock returns (see, e.g., Paye and Timmermann 2006; Hjalmarsson 2010) and a further investigation of EL method is needed to explore if predictor variable $x_t$ in Equation (3) can be allowed to have breaks; that is, both parameters $\theta$ and $\phi$ are unstable. Such investigations, including the issue mentioned in Remark 5, among others, are objects of ongoing research.

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## Conflict of interest

No potential conflict of interest was reported by the authors.

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## Appendix A: Mathematical Proofs

To prove Theorem 1, we consider the following predictive regression model with a structural break on an unknown date $T_1^0$ for $t = 1, \ldots, T$,

$$\begin{cases} y_t = (\alpha_1 + \beta_1 x_{t-1})1_{t \leq T_1^0} + (\alpha_2 + \beta_2 x_{t-1})1_{t > T_1^0} + u_t, \\ .x_t = \theta + \phi x_{t-1} + \sum_{j=0}^{\infty} \psi_j v_{t-j}. \end{cases}$$

We provide only the proof of Theorem 1 under the following setting:

$$\theta = 0 \text{ and } \phi = 1 - cT^{-1} \text{ for some } c \in \mathbb{R} \tag{A.1}$$

because the proofs for the other cases are straightforward. In particular, when $x_t$ is stationary, we can prove Theorem 1 based on the weak law of large numbers, the central limit theorem for martingales in Hall and Heyde (1980), and the standard arguments for establishing the profile EL method based on estimating equations in Qin and Lawless (1994). We state the following lemmas before proving Theorem 1: All limit statements are considered as $T \to \infty$ whenever there is no confusion.

The estimate of the break date $\hat{T}_1$ can be obtained using a global least squares criterion, as explained in Equation (5). Here, we consider the case in which $\hat{T}_1 < T_1^0$; that is, the estimated break date is located in the pre-$T_1^0$ subsample. Owing to symmetry, the same arguments can be applied to the case where $\hat{T}_1 > T_1^0$. We consider two subsamples: the pre-$\hat{T}_1$ subsample and the post-$\hat{T}_1$ subsample. We define the set $V(\epsilon)$ as follows:

$$V(\epsilon) = \{T_1 : |T_1 - T_1^0| < \epsilon, \forall \epsilon > 0\}.$$

From Proposition 1, $\Pr(\hat{T}_1 \in V(\epsilon)) \to 1$, regardless of whether $x_t$ is stationary or (nearly) integrated. Hence, it suffices to consider the behavior of EL methods for all $T_1 \in V(\epsilon)$. Let $m_1 \equiv [T_1/2] = [\lambda_1 T/2]$ and $m_2 \equiv [(T - T_1)/2] = [(1 - \lambda_1)T/2]$.

Lemma 1 *Under the conditions of Theorem 1 and Equation (A.1), we have*

$$\frac{1}{\sqrt{T}} \sum_{t=2}^{m_1} \tilde{H}_t(\beta_{1,0}) = \left( \frac{1}{\sqrt{T}} \sum_{t=2}^{m_1} \tilde{u}_t \right) \frac{\tilde{x}_{m_1-1}}{\sqrt{1 + \tilde{x}_{m_1-1}^2}} + o_p(1)$$

*and*

$$\frac{1}{\sqrt{T}} \sum_{t=T_1+2}^{T_1+m_2} \tilde{H}_t(\beta_{2,0}) = \left( \frac{1}{\sqrt{T}} \sum_{t=T_1+2}^{T_1+m_2} \tilde{u}_t \right) \frac{\tilde{x}_{T_1+m_2-1}}{\sqrt{1 + \tilde{x}_{T_1+m_2-1}^2}} + o_p(1),$$

*where* $\tilde{H}_t(\beta_{j,0}) = (\tilde{y}_t - \beta_{j,0}\tilde{x}_{t-1})\tilde{x}_{t-1}/(1 + \tilde{x}_{t-1}^2)^{1/2}$ *and* $\beta_{j,0}$ *denotes the true value of* $\beta_j$ *for* $j = 1, 2$.

**Proof of Lemma 1.**

It follows from Phillips (1987) under Equation (A.1),

$$T^{-1/2}x_{[Tr]} \Rightarrow K_c(r), \tag{A.2}$$

where $K_c(r) = \int_0^r e^{-(r-s)c} \mathrm{d}W_u(s)$ is a diffusion process and $W_u(s)$ is a one-dimensional Brownian motion with variance $\sigma_u^2 = \mathrm{Var}(u_t) + 2\Omega_1$, and $\Omega_1 = \sum_{k=2}^{\infty} \mathbf{E}[u_1 u_k]$. Here, "$\Rightarrow$" denotes a weak convergence in the Skorohod topology. From Equation (A.2), we obtain

$$\begin{aligned}
\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0}) &= \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\left(\sum_{j=1}^{t}\tilde{u}_j - \sum_{j=1}^{t-1}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} \\
&= \frac{1}{\sqrt{T}}\sum_{j=1}^{m_1}\tilde{u}_j\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}} + \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1-1}\left(\sum_{j=1}^{t}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} - \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\left(\sum_{j=1}^{t-1}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} \\
&= \left(\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{u}_t\right)\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}} + \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1-1}\left(\sum_{j=1}^{t}\tilde{u}_j\right)\left(\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} - \frac{\tilde{x}_t}{\sqrt{1+\tilde{x}_t^2}}\right) + o_p(1).
\end{aligned} \tag{A.3}$$

It follows from Taylor expansion that

$$\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} - \frac{\tilde{x}_t}{\sqrt{1+\tilde{x}_t^2}} = (1+\xi_t^2)^{-3/2}(\tilde{x}_{t-1} - \tilde{x}_t), \tag{A.4}$$

where $\xi_t$ lies between $\tilde{x}_{t-1}$ and $\tilde{x}_t$. From Equation (A.2), we have $|\tilde{x}_{t-1}|/t^a \xrightarrow{p} \infty$, $|\tilde{x}_t|/t^a \xrightarrow{p} \infty$, and $|\tilde{x}_{t-1} - \tilde{x}_t|/t^a \xrightarrow{p} 0$ for any $a \in (0, 1/2)$ as $t \to \infty$, thereby

$$|\xi_t|/t^a \xrightarrow{p} \infty \quad \text{forany } a \in (0, 1/2) \text{ as } t \to \infty. \tag{A.5}$$

By Equations (A.2)–(A.5), we have

$$\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0}) = \left(\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{u}_t\right)\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}} + o_p(1). \tag{A.6}$$

The post-$T_1$ subsample is divided into two parts around $T_1^0$. More precisely,

$$y_t = \begin{cases} \alpha_1 + \beta_1 x_{t-1} + u_t, & \text{for } t = T_1 + 1, \ldots, T_1^0, \\ \alpha_2 + \beta_2 x_{t-1} + u_t, & \text{for } t = T_1^0 + 1, \ldots, T, \end{cases}$$

and

$$y_{t+m_2} = \alpha_2 + \beta_2 x_{t-1} + u_t, \quad \text{for } t = T_1 + 1, \ldots, T_1 + m_2.$$

On the set $V(\epsilon)$, it holds that $(t + m_2) > T_1^0$ for $t = T_1 + 1, \ldots, T_1 + m_2$. Hence, $\tilde{y}_t = \beta_2 \tilde{x}_{t-1} + \tilde{u}_t$, where

$$\tilde{u}_t = \begin{cases} (u_t - u_{t+m_2}) + (\alpha_1 - \alpha_2) + (\beta_1 - \beta_2)x_{t-1}, & \text{for } t = T_1 + 1, \ldots, T_1^0, \\ (u_t - u_{t+m_2}), & \text{for } t = T_1^0 + 1, \ldots, T_1 + m_2. \end{cases}$$

It is straightforward to show that

$$\begin{aligned}
\frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\tilde{H}_t(\beta_{1,0}) &= \frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\left(\sum_{j=1}^{t}\tilde{u}_j - \sum_{j=1}^{t-1}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} \\
&= \frac{1}{\sqrt{T}}\sum_{j=1}^{T_1+m_2}\tilde{u}_j\frac{\tilde{x}_{T_1+m_2-1}}{\sqrt{1+\tilde{x}_{T_1+m_2-1}^2}} + \frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2-1}\left(\sum_{j=1}^{t}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} \\
&\quad - \frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\left(\sum_{j=1}^{t-1}\tilde{u}_j\right)\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} + \frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\left[(\alpha_1-\alpha_2)+(\beta_1-\beta_2)x_{t-1}\right]\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} \\
&= \left(\frac{1}{\sqrt{T}}\sum_{t=2}^{T_1+m_2}\tilde{u}_t\right)\frac{\tilde{x}_{T_1+m_2-1}}{\sqrt{1+\tilde{x}_{T_1+m_2-1}^2}} + \frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2-1}\left(\sum_{j=1}^{t}\tilde{u}_j\right)\left(\frac{\tilde{x}_{t-1}}{\sqrt{1+\tilde{x}_{t-1}^2}} - \frac{\tilde{x}_t}{\sqrt{1+\tilde{x}_t^2}}\right) + o_p(1),
\end{aligned} \tag{A.7}$$

where $T_1$ is in the set $V(\epsilon)$ with probability approaching 1; therefore, the number of terms in the summation $\sum_{T_1+2}^{T_1+m_2}$ is finite, which suggests that $T^{-1/2}\sum_{t=T_1+2}^{T_1+m_2}[(\alpha_1-\alpha_2)+(\beta_1-\beta_2)x_{t-1}]\tilde{x}_{t-1}/(1+\tilde{x}_{t-1}^2)^{1/2} \xrightarrow{p} 0$ because $m_2 = [(T-T_1)/2]$. Using Equations (A.2), (A.4), and (A.5) and (Appendix A), we have

$$\frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\tilde{H}_t(\beta_{2,0}) = \left(\frac{1}{\sqrt{T}}\sum_{t=T_1+2}^{T_1+m_2}\tilde{u}_t\right)\frac{\tilde{x}_{T_1+m_2-1}}{\sqrt{1+\tilde{x}_{T_1+m_2-1}^2}} + o_p(1). \tag{A.8}$$

Hence, the lemma follows from Equations (A.6) and (A.8). ■

Lemma 2 *Under the conditions of Theorem 1 and Equation (A.2), we have*

$$\frac{1}{T}\sum_{t=2}^{m_1}\tilde{H}_t^2(\beta_{1,0}) \xrightarrow{p} \Sigma \quad \text{and} \quad \frac{1}{T}\sum_{t=T_1+2}^{T_1+m_2}\tilde{H}_t^2(\beta_{2,0}) \xrightarrow{p} \Sigma,$$

*where* $\Sigma = \mathrm{E}[\tilde{u}_1^2]$.

**Proof of Lemma 2.**

Using Equations (A.2), (A.4), and (A.5), we have

$$\frac{1}{T}\sum_{t=2}^{m_1}\tilde{H}_t^2(\beta_{1,0}) = \frac{1}{T}\sum_{t=2}^{m_1}\tilde{u}_t^2\frac{\tilde{x}_{t-1}^2}{1+\tilde{x}_{t-1}^2} = \frac{1}{T}\sum_{t=2}^{m_1}\tilde{u}_t^2 + o_p(1) = \mathrm{E}[\tilde{u}_1^2] + o_p(1).$$

Similarly, we show that $T^{-1}\sum_{t=T_1+2}^{T_1+m_2}\tilde{H}_t^2(\beta_{2,0}) \xrightarrow{p} \Sigma$. Therefore, Lemma 2 holds. ■

Lemma 3 *Suppose that Condition A holds. Then,*

$$\max_{2 \le t \le m_1} ||\tilde{H}_t(\beta_{1,0})|| = O_p(T^{1/2}) \quad \text{and} \quad \max_{T_1+2 \le t \le T_1+m_2} ||\tilde{H}_t(\beta_{2,0})|| = O_p(T^{1/2}).$$

**Proof of Lemma 3.**

Clearly, $\mathbf{E}[\tilde{H}_t(\beta_{1,0})] = 0$ and $\mathbf{E}[\tilde{H}_t(\beta_{1,0})^2] \le \mathbf{E}[\tilde{u}_t^2] = O(1)$, implying that

$$\left(\mathbf{E}[\max_{2 \le t \le m_1} ||\tilde{H}_t(\beta_{1,0})||]\right)^2 \le \mathbf{E}[(\max_{2 \le t \le m_1} ||\tilde{H}_t(\beta_{1,0})||)^2]$$
$$\le \sum_{t=2}^{m_1} \mathbf{E}[\tilde{H}_t(\beta_{1,0})^2] = O(T),$$

where the first inequality is implied by Jensen's inequality. As a result,

$$\max_{2 \le t \le m_1} ||\tilde{H}_t(\beta_{1,0})|| = O_p(T^{1/2}).$$

In a similar way, we can show that

$$\max_{T_1+2 \le t \le T_1+m_1} ||\tilde{H}_t(\beta_{2,0})|| = O_p(T^{1/2}).$$

This completes the proof of Lemma 3. ■

**Proof of Theorem 1.** Using Lemmas 1–3 and the standard arguments in the proof of the EL method (Owen 2001, Chapter 11), both $\tilde{l}_1(\beta_{1,0})$ and $\tilde{l}_2(\beta_{2,0})$ converge in distribution to a chi-square limit with one degree of freedom. Consequently, the EL statistic in each regime is independent of the others, suggesting that their summation goes to $\chi^2(2)$, which completes the proof of Theorem 1. ■

**Proof of Theorem 2.**

i. $|\phi| < 1$ independent of $T$ (stationary case): Under the alternative $\mathbb{H}_1 : \beta_{j,1} = \beta_{j,0} - bT^{-1/2}$ for some constant $b \in \mathbb{R}$ and $j \in \{1, 2\}$,

$$\tilde{y}_t - \beta_{j,0}\tilde{x}_{t-1} = \tilde{y}_t - \beta_{j,1}\tilde{x}_{t-1} + \beta_{j,1}\tilde{x}_{t-1} - \beta_{j,0}\tilde{x}_{t-1}$$
$$= \tilde{u}_t + (\beta_{j,1} - \beta_{j,0})\tilde{x}_{t-1}$$
$$= \tilde{u}_t - bT^{-1/2}\tilde{x}_{t-1}.$$

Then,

$$\tilde{H}_t(\beta_{1,0}) = \tilde{H}_t(\beta_{1,0} - bT^{-1/2}) - bT^{-1/2}\tilde{x}_{t-1}\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}},$$

and

$$\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0}) = \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0} - bT^{-1/2}) - \left(\frac{b}{T}\sum_{t=2}^{m_1}\tilde{x}_{t-1}\right)\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}}$$
$$= \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0} - bT^{-1/2}) + \gamma_{11} + o_p(1),$$

where $\gamma_{11} = b[(-(1-\phi^{m_1})/(1-\phi))\mu + (1-\phi^{m_1})\lim_{t\to\infty}\mathbf{E}[x_{t-1}]]$. Moreover,

$$\frac{1}{T}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{1,0})^2 = \frac{1}{T}\sum_{t=2}^{m_1}\left[\tilde{H}_t(\beta_{1,0} - bT^{-1/2}) + bT^{-1/2}\tilde{x}_{t-1}\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}}\right]^2$$
$$= \frac{1}{T}\sum_{t=2}^{m_1}[\tilde{H}_t(\beta_{1,0} - bT^{-1/2})]^2 + o_p(1) \xrightarrow{p} \Sigma.$$

Using Lemmas 1–3 and Theorem 1, we have

$$\tilde{l}_1(\beta_{1,0}) \xrightarrow{d} \chi^2(v_{11}^2),$$

where $v_{11} = \Sigma^{-1/2}\gamma_{11}$. Similarly, we can show that $\tilde{l}_1(\beta_{2,0}) \xrightarrow{d} \chi^2(v_{12}^2)$ with $v_{12} = \Sigma^{-1/2}\gamma_{12}$ and $\gamma_{12} = b[(-(1-\phi^{m_2})/(1-\phi))\mu + (1-\phi^{m_2})\lim_{t\to\infty}\mathbf{E}[x_{t-1}]]$.

ii. $\phi = 1 - c/T$ for some $c \geq 0$ (NI(1) case): Under the alternative $\mathbb{H}_1 : \beta_{j,1} = \beta_{j,0} - bT^{-1}$ for some constant $b \in \mathbb{R}$ and $j \in \{1, 2\}$,

$$\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0}) = \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0} - bT^{-1/2}) + \left(\frac{b}{T^{3/2}}\sum_{t=2}^{m_1}\tilde{x}_{t-1}\right)\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}}$$
$$= \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0} - bT^{-1/2}) + \gamma_{2j} + o_p(1),$$

where $\gamma_{21} = b[2K_b(\lambda_1/2) - K_b(1)]$, $\gamma_{22} = b[2K_b((1-\lambda_1)/2) - K_b(\lambda_1) - K_b(1)]$, and $K_b(r) = \int_0^r e^{-(r-s)b}\mathrm{d}W_u(s)$ with $W_u(s)$ defined in the proof of Lemma 1. Furthermore,

$$\frac{1}{T}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0})^2 = \frac{1}{T}\sum_{t=2}^{m_1}\left[\tilde{H}_t(\beta_{j,0} - bT^{-1/2}) + bT^{-1}\tilde{x}_{t-1}\frac{\tilde{x}_{m_1-1}}{\sqrt{1+\tilde{x}_{m_1-1}^2}}\right]^2$$
$$= \frac{1}{T}\sum_{t=2}^{m_1}[\tilde{H}_t(\beta_{j,0} - bT^{-1/2})]^2 + o_p(1) \xrightarrow{p} \Sigma.$$

Then, we have

$$\tilde{l}_1(\beta_{j,0}) \xrightarrow{d} \chi^2(v_{2j}^2)$$

where $v_{2j} = \Sigma^{-1/2}\gamma_{2j}$ for $j = 1, 2$.

iii. $\phi = 1$ (I(1) case): Under the alternative $\mathbb{H}_1 : \beta_{j,1} = \beta_{j,0} - bT^{-1}$ for some constant $b \in \mathbb{R}$ and $j \in \{1, 2\}$,

$$\frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0}) = \frac{1}{\sqrt{T}}\sum_{t=2}^{m_1}\tilde{H}_t(\beta_{j,0} - bT^{-1/2}) + \gamma_{3j} + o_p(1),$$

where $\gamma_{31} = b[2K_b^*(\lambda_1/2) - K_b^*(1)]$, $\gamma_{32} = b[2K_b^*((1-\lambda_1)/2) - K_b^*(\lambda_1) - K_b^*(1)]$, and $K_b^*(r) = \Xi\int_0^r W_u(s)\mathrm{d}s$ with $\Xi = \sigma_v\sum_{j=0}^{\infty}\psi_j = \sigma_v\psi(1)$. Then, we have

$$\tilde{l}_1(\beta_{j,0}) \xrightarrow{d} \chi^2(v_{3j}^2),$$

where $v_{3j} = \Sigma^{-1/2}\gamma_{3j}$ for $j = 1, 2$. It completes the proof of Theorem 2. ■

**Proof of Proposition 1.** For the proof, see Proposition 4 in Bai and Perron (1998) and Proposition 2 in Kurozumi and Arai (2007a). ■

**Proof of Theorem 3.** It can be shown in the same way as in Theorem 1. ■

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